A Thesis on

DESIGN OF HEAT INTEGRATED MULTIPLE EFFECT EVAPORATOR SYSTEM

Submitted by

GHOSHNA JYOTI

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DR. SHABINA KHANAM

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Department of Chemical Engineering

National Institute of Technology

Rourkela, Orissa

DEPARTMENT OF CHEMICAL ENGINEERING

NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA

ORISSA, INDIA - 769008

CERTIFICATE

This is to certify that the thesis titled "***DESIGN OF HEAT INTEGRATED MULTIPLE EFFECT EVAPORATOR SYSTEM***", submitted to the National Institute of Technology, Rourkela by **Ghoshna Jyoti**, Roll No. **210CH1201** for the award of the degree of **Master of Technology** in Chemical Engineering, is a bona fide record of research work under my supervision and guidance. The candidate has fulfilled all the prescribed requirements. The thesis, which is based on candidate's own work, has not been submitted elsewhere for a degree/diploma.

In my opinion, the thesis is of standard required for the award of a Master of Technology degree in Chemical Engineering. To the best of my knowledge, she bears a good moral character and decent behavior.

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Dr Shabina Khanam

Department of chemical enginnering

National Institute of Technolgy

Rourkela-769008

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Ghoshna Jyoti

Roll. No.: 210CH1201

4th Semester, M. Tech

Chemical Engineering Dept.

CONTENTS

ABSTRACT

Evaporators can minimize the production of regulated waste residues, and increase the potential for recovering valuable materials from those wastes. Multiple-effect evaporators (MEEs) are common to industries that concentrate different products, regenerate solvents, or separate solid-liquid mixtures. Process integration can help to choose the best configuration of MEE in order to achieve a more efficient process in the sense of energy use.

In present work a number of configurations and difficulties of MEE system such as condensate flashing, vapour bleeding, steam splitting, preheating of liquor using condensate, variable physical properties and boiling point rise are taken into consideration to develop different models of evaporation system. In the present work seven effect evaporator system of typical Indian pulp and paper industry is considered for analysis based on above configurations. These systems is described by a set of nonlinear algebraic equations that include total and solute mass balances, energy balances, heat transfer rate equations, and the composition and temperature dependence of relevant thermodynamic properties such as vapour pressures and enthalpies. The models are solved using ‘system of nonlinear equations’. Pinch analysis of the MEE network is also done.

Economic evaluation to optimize the number of flash tanks is carried out for seven effect evaporator system. The two different types of configuration of vapor bleeding are considered and comparison of both configurations is done. Considering the optimum number of flash tanks and the best configuration of vapor bleeding, a system was designed. Considering the maximum possible number of flash tanks and preheating of liquor using condensate, a final system was designed. This modified design enhances the steam economy by 23.77% and reduces the steam consumption by 36.76% in comparison to simple system.

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

Symbol used	Parameter
F	Feed flow rate (kg/s)
V_0	Steam flow rate (kg/s)
L	Flow rate of liquor stream (kg/s)
V	Flow rate of vapor stream (kg/s)
CS	Condensate flow rate of steam/vapor (kg/s)
H	Enthalpy of liquor (KJ/kg)
H	Enthalpy of vapor (KJ/kg)
λ	Heat of vaporization/latent heat (KJ/kg)
A	Heat transfer area of an effect (m^2)
U	Overall heat transfer coefficient (KW/m^2K)
T	Temperature (˚C)
ΔT	Temperature drop (˚C)
X	Solid concentration
Q	Heat flux (KW/m^2)
BPR	Boiling point rise (˚C)
X_{DM}	Dry matter concentration
Cp	Specific heat (KJ/kg °C)
V’	Bled vapor flow rate (kg/s)

Subscripts

1 – 7	Effect number
F	Feed
0	Steam
L	Liquor
V	Vapor

CHAPTER 1

INTRODUCTION

CHAPTER 1

INTRODUCTION

Evaporators are integral part of a number of process industries namely Pulp & Paper, Chlor-alkali, Sugar, Pharmaceuticals, Desalination, Dairy and Food processing, etc. The Pulp and Paper industry, which is the focus of the present investigation, uses the Kraft Process to convert wood chips into pulp. The Kraft process consists of multiple effect evaporators (MEE) system as one of the major section. The evaporator house of a Pulp and Paper industry consumes about 24-30% of its total energy and makes it as an energy intensive section (Rao and Kumar, 1985).

With the development of falling film evaporator which work under a low temperature difference, more and more Indian Pulp and Paper industry have started inducting these evaporators into their MEE system. Thus, present study also considers flat falling film evaporator system. The energy efficiency of MEE system can be enhanced by inducting flashing, splitting and vapor bleeding. In the present work seven effect evaporator system of typical Indian pulp and paper industry is considered for analyses based on above configurations.

Over last seven decades, mathematical models of MEE systems have been used to analyze these complex systems. Some of these have been developed by Holland (1975), Lambert et al. (1987), El-Dessouky et al. (2000) and Bhagrava et al. (2008). These models are based on set of linear and non-linear equations. Amongst these models Bhargava et al. (2008) proposed a model using generalized cascade algorithm in which model of an evaporator body is solved repeatedly to address the different operating configurations of a MEE system. However, other investigators proposed equation based models where the whole set of governing equations of the model needs to be changed to address the new operating configuration. These two strategies of modeling are successfully applied to simulate a number of MEE systems.

These models also use complex transport phenomena based mathematical models or empirical models for the prediction of overall heat transfer coefficients (U) of evaporators as a function of liquor flow rate, liquor concentration, physico-thermal properties of evaporating liquor and type of evaporator employed. On the other hand, Khanam and Mohanty (2011) proposed linear model based on principles of process integration. This model worked on the assumption of equal ΔT in each effect and thus, eliminated the requirement of U in the model.

Though all these models account complexities of real MEE system such as variation in physical properties, flashing, splitting and bleeding these do not propose methodology to optimize the performance of the system considering flashing as well as vapor bleeding. In other words, these models were developed with condensate flashing in which positions of flash tanks were fixed. These did not account optimum number of flash tanks, its position in the MEE system, performance of each flash tank, etc. These also did not consider different configurations for vapor bleeding to optimize the economy of the system.

Thus, under the above backdrop it appears that there is a scope for development of mathematical model which can accommodate different operating configurations using different position of flash tanks as well as preheaters. Based on the above discussions the present work has been planned with following objectives:

1. To develop model for seven effect evaporator system with variation in physical properties of liquor, condensate and vapor, boiling point rise and for different operating configuration such as steam splitting, condensate flashing, vapor bleeding, etc.
2. To compute contribution of different flash tanks towards total evaporation and thus to optimize number of flash tanks in the system based on economic analysis.
3. To extract steam data from seven effect evaporator system and apply pinch analysis to these data.
4. To compare the steam economy predicted by models of different configurations and to propose modified design for seven effect evaporator system.

CHAPTER 2

LITERATURE REVIEW

CHAPTER 2
LITERATURE REVIEW

A detailed literature review on different aspects of multiple effect evaporator (MEE) system has been reported in this Chapter. Many investigators have published on different aspects such as mathematical modeling, design, operation, optimal number of effects and optimal feed flow sequence, etc. As the present work is related to the design of MEE system, a literature review covering all aspects of the present work is presented in this Chapter. This chapter is divided into six sections:

1) Thermo physical properties of black liquor solution
2) Heat transfer coefficient of falling film evaporator
3) Modeling of multiple effect evaporators
4) Energy reduction schemes (ERSs)
5) Simulation and optimization of multiple effect evaporators
6) Aspen pinch analysis

2.1 THERMO PHYSICAL PROPERTIES OF BLACK LIQUOR SOLUTION

There are several physical and thermal properties that are important to black liquor evaporator design and operation. These properties are boiling point rise, specific heat, latent heat of vaporization and density. Black liquor is typically about one-third inorganic and two thirds organic materials. A brief review of literature on above properties is presented below:

Regested (1951) developed a correlation for specific heat capacity of black liquor as a function of total solid content (%S) of the liquid. He considered the dependence of specific heat on the temperature to be negligible.

$$C_{pL} = 4187\left[1 - 0.0054\,[\%S]\right] \tag{2.1}$$

Hultin (1968) proposed the following expression for BPR and specific heat of black liquor as a function of solid concentration :

$$C_{pL} = 0.96 - (4.5 \times 10^{-3})[\%S] \tag{2.2}$$

$$BPR = \frac{K[\%S]}{100-[\%S]} \tag{2.3}$$

where, K is a constant and just equivalent to the BPR at 50% solid concentration.

Zaman and Fricke (1996) proposed the correlation of specific heat of slash pine Kraft black liquor as given in Eq (2.4) and also studied the BPR of slash pine Kraft black liquors for a wide range of solid concentrations (up to 85%) and proposed the correlation is shown in Eqs (2.5) and (2.6) :

$$C_{pL} = 3.98 + (6.19 \times 10^{-4})T + (c + dT)x \qquad (2.4)$$

Where, c and d are concentration-dependent constants that have been correlated to the pulping conditions for the liquors.

$$BPR = (a_1 + b_1 Pr)\left(\frac{x}{1-x}\right) \text{for } x < 0.65 \qquad (2.5)$$

$$BPR = [(a_2 + b_2 Pr) + (a_3 + b_3 Pr)]\left[\frac{x}{1-x}\right] \text{for } x \geq 0.65 \qquad (2.6)$$

Where, a_1, b_1, a_2, b_2, a_3 and b_3 are experimentally determined constants.

Regested (1951) proposed following expression for the computation of density of black liquor, as a function of solids temperature (T_s) and temperature of liquor (T_L).

$$\rho = 1007 + 6T_s - 0.495T_L \qquad (2.7)$$

Bhargavaa et al. (2008) developed the expression for the boiling point rise and spcific heat of the solutions as a function of solid concentration (x)

$$\text{BPR} = 20\,(0.1 + x)^2 \qquad (2.8)$$

The heat capacity of the liquid solution is calculated from

$$C_P = C_1\,(1 - C_4 x) \qquad (2.9)$$

Where, values of coefficients C1 and C4 are 4.187 and 0.54, respectively.

2.2 HEAT TRANSFER COEFFICIENT OF FALLING FILM EVAPORATOR

Falling film evaporators are especially popular in the food and paper industry where many substances are heat sensitive. A thin film of the product to be concentrated trickles down inside of heat exchanging tubes. Steam condenses on the outside of the tubes supplying the required energy to the inside of the tubes.

Muller-Steinhagen and Branch (1997) performed a large number of experiments with New Zealand Forest Products Kraft black liquor to measure heat transfer coefficients and fouling rates during convective and sub-cooled flow boiling heat transfer as a function of surface temperature, bulk temperature, velocity and solids concentration. They presented results from experiments with two chemical fouling inhibitors with Teflon surface coating on plate and frame heat exchangers. They analyzed the system with respect to composition and process conditions. They developed a deposition model with the experimental data and compared with the assumption of chemical reaction-controlled fouling.

For laminar flow, obtained the following approximate relation:

$$N_{u,lam} = C_1 Re^{0.45} \tag{2.10}$$

For turbulent flow, approximated the Nusselt-Reynolds relation by

$$N_{u,turb} = C_2\ Re^{0.8} \tag{2.11}$$

Pacheco and Frioni (2004) observed the evaporation of sugar cane juice in a climbing/falling film evaporator and performed experiments in single-effect process with sugar juice concentrations varying from 15 to 40 Brix and noted that in a traditional multiple-effect evaporator used in the cane sugar industry, this concentration ranged from that of the inlet of the first effect (15%) to that of the outlet of the third effect (40%). The variation in overall heat-transfer coefficient related to juice concentration was calculated, along with surface-heat coefficients on the solution side and temperatures of the heating surfaces. They proposed a relative, more general, overall heat transfer index.

Prost et al. (2006) determined the heat transfer parameters of a single effect evaporator under different operating conditions in order to extrapolate them to a multiple effect unit. The conditions of each effect of a multiple effect evaporator were simulated varying feed concentration and pressure. The obtained values were correlated by means of an equation that links the heat transfer coefficient with the fluid properties, geometric parameters and flow conditions. Comparison with existing correlations was carried out.

The proposed following equation for the dimensionless heat transfer coefficient:

$$h^{+} = h_i \left(\frac{\mu_L^2}{\rho_L^2 k_L^3 g}\right)^{1/3} \tag{2.12}$$

Chen and Jebson (1997) used a pilot scale single-tube falling film evaporator (2 meters length of heating tube) to understand the mechanism of evaporation. They obtained results from commercial milk evaporators which were used to select operating conditions on the pilot evaporator. They carried out the study using the Newtonian liquids: water and sugar solutions and observed that the overall heat transfer coefficients were affected mainly by temperature difference between the liquid evaporating and the steam condensing temperatures, evaporating temperature, irrigation density, liquid viscosity and the heating tube length.

Bhargavaa et al. (2008) developed the mathematical model of overall heat transfer coefficients of different effects was

$$\frac{U_c}{U_{max}} = a\left(\frac{\Delta T}{40}\right)^b \left(\frac{x_{avg}}{0.6}\right)^c \times \left(\frac{F_{avg}}{25}\right)^d \quad (2.13)$$

Where a,b,c and d are experimentally determined constants.

Adib et al. (2009) studied process parameters affecting boiling heat transfer coefficient (h) in the falling film evaporator and these are: the dry matter concentration X_{DM} (or Brix for sugar solution), the evaporating temperature (θ_L) or pressure (P) taking into account the boiling point elevation (BPE), the heat flux or the temperature difference between the heated surface and boiling liquid temperature ($\Delta\theta$) and the specific mass flow rate per unit of perimeter length (Γ). The nature of heated surface is kept constant (stainless steel) and the effect of the emitted vapour velocity is not taken into account in our study. The variations of h with ϕ or $\Delta\theta$, are given for pure water and sugar solutions at different concentrations (10%, 30%, 50% and 70%), and interpreted in relation with the two boilingregimes (non-nucleate and nucleate).

For non-nucleate regime ($2 \le \phi \le 10$ kW m^{-2}), and for dilute sugar solution ($10 \le X_{DM} \le$ 30%);

$$h = 30.6\, X^{-0.25} \Gamma^{0.14} \theta_L^{1.22} \quad (2.14)$$

For nucleate regime ($20 \le \phi \le 80$ kW m^{-2}), and for middle concentrated sugar solution (30 $\le X_{DM} \le 70$%);

$$h = 28.34\, \emptyset^{0.34} X^{-0.53} \Gamma^{0.2} \theta_L^{1.24} \quad (2.15)$$

Shrivastava (2011) developed the mathematical model of overall heat transfer coefficients of different effects based on plant data of seven effect evaporator system.

$$\frac{U_c}{U_{max}} = a\left(\frac{\Delta T}{\Delta T_{max}}\right)^b \left(\frac{x_{avg}}{x_{max}}\right)^c \times \left(\frac{F_{avg}}{F_{max}}\right)^d \quad (2.16)$$

Where, a, b, c and d are experimentally determined constants.

2.3 MODELLING OF MULTIPLE EFFECT EVAPORATORS

Lambert et al. (1987) presented a model which was based on the nonlinear enthalpy relationships and boiling point rise. Curve fitting techniques and interpolation were used to reach these relationships.

Hillenbrand and Westerberg (1988) reported on evaporation system synthesis and developed a model to compute the utility consumption explicitly for multiple-effect evaporator systems that exchanged sensible heat with streams that were both inside and outside the evaporation system. A modified "grand composite curve" (MGCC) was developed to plot the temperature for placing an evaporator vs. the maximum amount of such sensible heat that could be exchanged. The simplified model and MGCC were then used to discover the approximate best temperature at which single evaporator effect was to be placed which partially motivated the evaporation system synthesis approach.

Miranda and Simpson (2005) described a phenomenological, stationary and dynamic model of a multiple effect evaporator for simulation and control purposes. The model includes empirical knowledge about thermo-physical properties that must be characterized into a thermodynamic equilibrium. The developed model consists of differential and algebraic equations that are validated using a parameter sensitivities method that uses data collected from the industrial plant. The simulation results showed a qualitatively acceptable behavior.

Kaya and Sarac (2007) developed a mathematical model for multiple-effect evaporators. These evaporators had cocurrent, countercurrent and parallel flow operation options. Each operation was investigated with and without pre-heaters. The effect of pre-heating on evaporation process was investigated from the point of energy economy. A sugar factory's data was used with the applied models as a case study.

Bhargava et al. (2008a, 2008b) developed a non-linear mathematical model for the analysis of multiple effect evaporators (MEE) system. This model was capable of simulating process of evaporation and takes into account variations in -boiling point rise due to variation in concentration and temperature of liquor, overall heat transfer coefficient of effects and physico-thermal property of the liquor. This model was developed for a Septuple effect flat falling film evaporator system with backward feed flow sequence being used for concentrating weak black liquor. This system supported different operating strategies such as steam splitting and condensate, feed and product flashing. Based on mass and energy balance around an effect a cubic polynomial was developed and solved repeatedly in a predetermined sequence using generalized cascade algorithm.

Khanam and Mohanty (2010, 2011) proposed a simplified scalable mathematical model based on concepts of stream analysis, temperature paths and internal heat exchange for synthesis of multiple effect evaporator systems. In this model fresh feed was assumed to be composed of product and number of condensate streams, which come out from different effects and these are treated as separate streams. For the present work a septuple effect flat falling film evaporator system, being used for concentrating black liquor in an Indian Kraft Pulp and Paper mill, was considered. The present model consists of linear equations, which are automatically generated through temperature path. Khanam and Mohanty (2010) considered flashing in the model and showed the trade-off between annual capital and operating costs, which decides optimum number of flash tanks as well as their positions in the MEE system.

Gautami and Khanam (2012) developed mathematical models based on set of nonlinear equations have been for the synthesis of multiple effect evaporator (MEE) systems. A number of configurations and complexities of real MEE system such as condensate, feed and productflashing, vapor bleeding, steam splitting, variable physical properties and boiling point rise were accounted to develop of different models.

Kumar et al. (2012) reported a wide range of mathematical models for multiple effect evaporators in process industry including paper industry. They found that dynamic behavior of multi-effect evaporator system of a paper industry could be obtained by disturbing the feed flow rate, feed concentration, live steam temperature and feed temperature and for that an unsteady-state model for the Multi-effect evaporator system was developed. Each effect in the process was represented by a number of variables which were related by energy and material balance equations for the feed, product and vapor flow. A generalized mathematical model which could be applied to any number of effects and all kinds of feeding arrangements like forward feed, backward feed, mixed feed and spilt feeding the MEE system with simple modifications was finally obtained. Finally model for mixed feed sextuple effect falling film evaporators system was solved using MATLAB.

2.4 ENERGY REDUCTION SCHEMES (ERSs)

The steam consumption for the MEE system can be reduced by incorporating different ERSs. These ERSs are induction of flashing, vapor bleeding, heating up liquor using condensate, etc., in the MEE system.

Khanam and Mohanty (2010) developed different energy reduction schemes (ERSs), used to reduce the consumption of steam for a multiple effect evaporator (MEE) system. These ERSs were condensate-, feed- and product- flashing and vapor bleeding.
El-Dessouky and Ettouney (1999) analyzed and compared several operating configurations including the parallelflow (MEE–P), the parallel/cross flow (MEE–PC), and systems combined with thermal (TVC) or mechanical (MVC)vapor compressionon the MEE system.

2.5 SIMULATION AND OPTIMIZATION OF MULTIPLE EFFECT EVAPORATORS

In literature many investigators used number of technique for optimization of the evaporator system. The design of the evaporation processis concerned more about using the minimum amount of steam to evaporate large amounts of water. Simulation of the process allows better design, operation and insight into the operation of the process from which an optimal operating condition and advanced control strategy are reached.
Nishitani and Kunugita (1979) discussed the optimization of the flow-pattern for a multiple effect evaporator system. They described a new program to solve the design problem for various flow-patterns with no stream mixing or splitting. They generated the set of non-inferior flow-patterns by enumerating one-by-one for all flow-patterns. This method works well in synthesizing multiple effect evaporator configurations.
Simpson et al. (2008) proposed a new economic evaluation procedure to optimize the design and operation of multiple effect evaporators and compared it with the traditional chemical engineering approach of total cost minimization. The proposed strategy incorporates a quality factor expressed as a function of lycopene concentration on the final product to find the optimal number of effects and operating conditions through the maximization of the net present value.
Higa et al. (2009) studied a few previous works on MEE and found that the vapor generated during the evaporation operation (vegetal vapor) could be used as a heating source from extractions to process and that the energy recovery was usually larger when extractions were practiced in the last effects of the operation. A study was carried out by them to define equations that could be used as a reference for thermal integration projects, including MEEs. These equations were also helpful for elaborating a systematic way to apply pinch analysis in sugar plant with an algorithm.

Khademi et al. (2009) studied the steady-state simulation and optimization of a six-effect evaporator and the provision of its relevant software package and investigated the modeling equations of each of the existing building blocks written in a steady-state conditions which had been used for simulation and process optimization of the entire vaporizing unit while exercising the simplifying assumptions. They presented effect of different parameters on consumed steam produced distilled water and GOR (gained output ratio) along with the optimization of feed mass flowrate, condenser pressure and operating time. They found simulation results were good agreement with design data.

Pimenta (1993) presented APC based simulator of the steady-state behaviour of multiple-effect calandria (or equivalent) evaporators. They found that the package, 'MULTEVA' could be applied in studies concerning thermodynamic design, in the analysis of alternative forms of operation and in the monitoring of unit efficiency. They created a database on the relevant thermodynamical and physical properties of the solute, solvent and solution with read write capacities which proved its efficiency in industrial applications of sugar liquor evaporation.

2.6 ASPEN PINCH ANALYSIS

Pinch Analysis presents a simple methodology for systematically analyzing chemical processes and surrounding utility systems with the help of First and Second laws of Thermodynamics (Linnhoff et al., 1982). In practice a minimum temperature difference (ΔT_{min}) has to be maintained between the 'hot' process streams (which have to be cooled to specified temperatures) and 'cold' process streams (which have to be heated to specified temperatures). The temperature level at which ΔT_{min} is observed in the process is referred to as 'Pinch Point'. The pinch defines the minimum driving force (ΔT_{min}) allowed in the exchanger unit. The amount of excess heat available at the mill can be estimated by using pinch analysis. Pinch analysis is a method to investigate the minimum heating and cooling load of the mill in order to take energy-efficiency measures. The pinch analysis divides the energy system into two parts: first part (above the pinch temperature) with a heat deficit and second part (below the pinch) with a heat surplus. The analysis shows whether pinch violations exist in the mill, i.e. if the pinch rules below are violated (Olsson 2009):

1. No cold utility should be used above the pinch temperature,
2. No hot utility should be used below the pinch temperature, and

3. Heat should not be transferred from a stream above the pinch temperature to a stream below the pinch temperature.

Pinch Technology has been extensively used to improve energy efficiency of various processes including Petrochemicals, Petroleum, Bulk Chemicals, Pulp and paper, Sugar, Alumina, Food Processing etc.

Axelsson et al, (2006) explored the opportunities for heat integration in order to create a steam surplus. The steam surplus gives opportunities for increased power generation or lignin extraction. They explored the technical and economic consequences of using the steam surplus and investigated two different approaches for creating a steam surplus 1) conventional measures and 2) process integrated evaporation.

Festin and Mora (2009) presented a pinch analysis of one part of a thermo-mechanical pulp (TMP) mill, Norske Skog Skogn,. They studied the improvement of process integration and to decrease the steam demand of the mill. Additionally, they studied the effect of decreasing the electricity consumption for two different scenarios: when certain amount of the electricity-intensive mechanical pulp was replaced with recycled paper and fillers and/or when implementing more energy efficient refining.

CHAPTER 3

PROBLEM STATEMENT

CHAPTER 3

PROBLEM STATEMENT

The present investigation deals with the modeling and simulation of multiple effect evaporator (MEE) system. In this Chapter the MFE system used for concentrating black liquor and its typical operating parameters are described.

3.1 PROBLEM STATEMENT

The MEE system that has been considered in this work is a seven effect evaporator operating in a typical Indian Kraft pulp and paper mill. These effects are flat falling film evaporators. The system is used in the paper mill for concentrating non-wood (straw) black liquor which is a by-product of the raw material digesting process. It contains inorganic spent cooking materials which are typically recovered by evaporation and incineration. The schematic diagram of the system is shown in Figure 3.1.

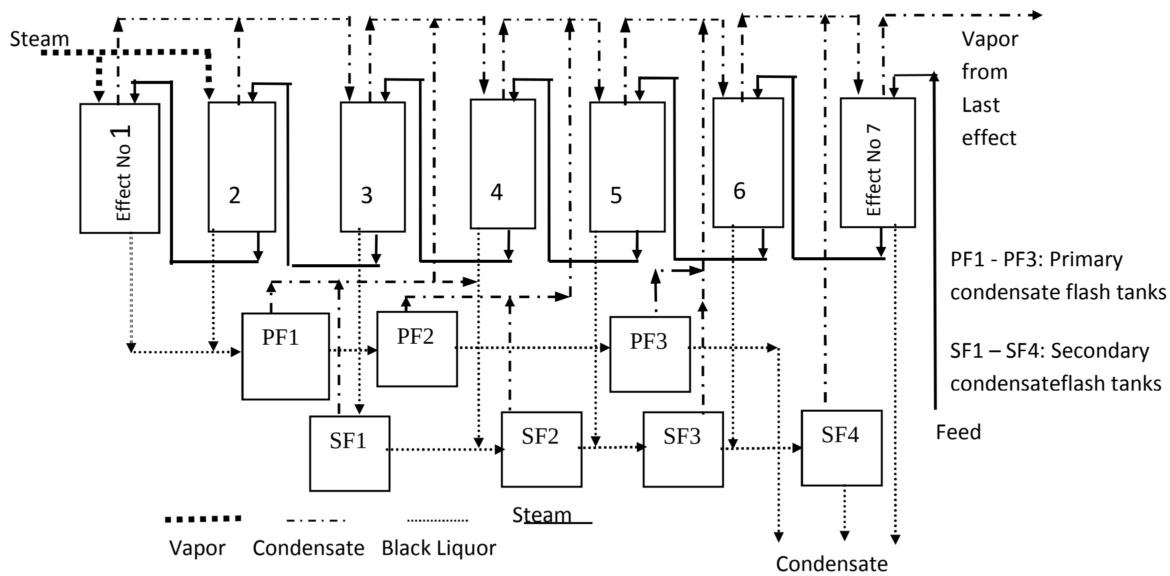

Figure 3.1 Schematic diagram of the seven effect system

The feed flow sequence followed in the system is backward that is the feed is initially fed to 7th effect, from there it goes to 6th effect and so on and finally the concentrated product is obtained from the first effect. Live steam is fed to the first and second effect thus these effects are operated at almost equal temperature. The steam going into first effect is 7 °C colder than that into second effect. Condensate flashing is employed in the system to generate auxiliary vapour which is then used to enhance the overall steam economy of the system. The base case operating parameters of the seven effect evaporator system are given in Table 3.1.

Table 3.1: Operating parameters of seven effect evaporator system

S. no.	Parameter(s)	Value(s)
1.	Total number of effects	7
2.	Number of effects supplied with live steam	2
3.	Live steam temperature in effect 1	140˚C
4.	Live steam temperature in effect 2	147˚C
5.	Inlet concentration of black liquor	0.118
6.	Inlet temperature of black liquor	64.7˚C
7.	Feed flow rate of black liquor	56,200 kg/hr
8.	Vapour temperature of last effect	52˚C
9.	Feed flow sequence	Backward
10.	Area of first and second effect	540 m^2
11.	Area of third to sixth effect	660 m^2
12.	Area of seventh effect	690 m^2

CHAPTER 4

DEVELOPMENT OF MODEL

CHAPTER 4
DEVELOPMENT OF MODEL

A model for seven effect evaporator system, used for concentrating black liquor solution and described in chapter 3, is developed. For the present investigation as most of the models use temperature dependent physico-thermal properties of liquor/fluids a number of correlations for the prediction of physico-thermal properties of black liquor solution and condensate (in present case water) are developed.

4.1 DEVELOPMENT OF CORRELATIONS

As steam/vapor enters different effects at different temperature, the properties of steam/vapor and condensate also vary with temperature. Thus, temperature dependent expressions of heat of vaporization and enthalpy are required to be developed. For this purpose data of heat of vaporization, enthalpy of water and enthalpy of steam over the temperature range of 52-148°C, obtained from steam table, are plotted. A second order polynomial and linear trends are fitted on heat of vaporization and enthalpy curve as shown in Figure 4.1, 4.2, and 4.3, respectively. The developed expressions of heat of vaporization and enthalpy are shown through following equations:

$$\lambda = -0.003\mathrm{T}^2 - 2.062\mathrm{T} + 2493 \tag{4.1}$$

$$\mathrm{h} = 4.222\mathrm{T} - 2.6593 \tag{4.2}$$

$$\mathrm{H} = -0.0028\mathrm{T}^2 + 2.1093\mathrm{T} + 2493.3 \tag{4.3}$$

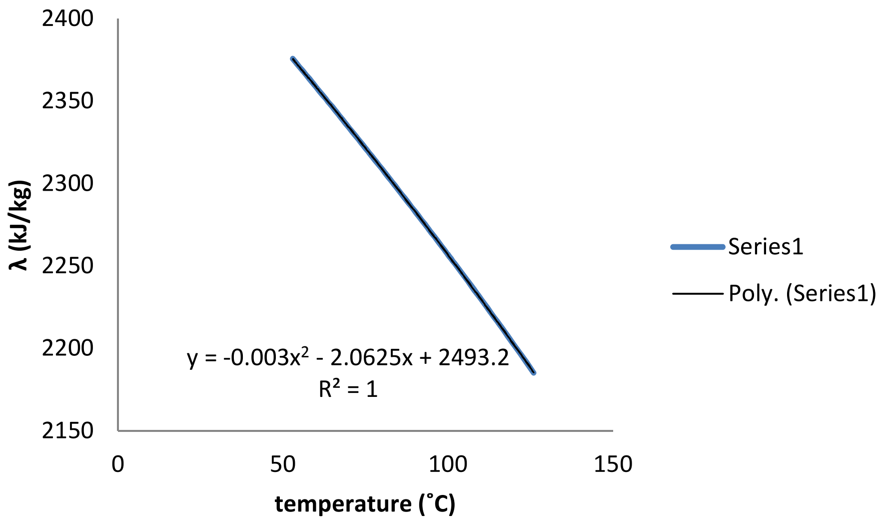

Figure 4.1: Correlation of heat of vaporisation

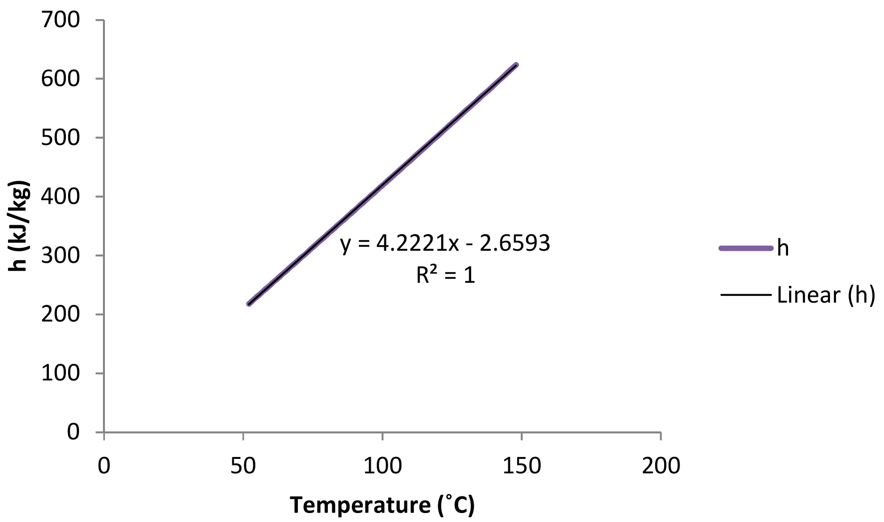

Figure. 4.2: Correlation of enthalpy of condensate

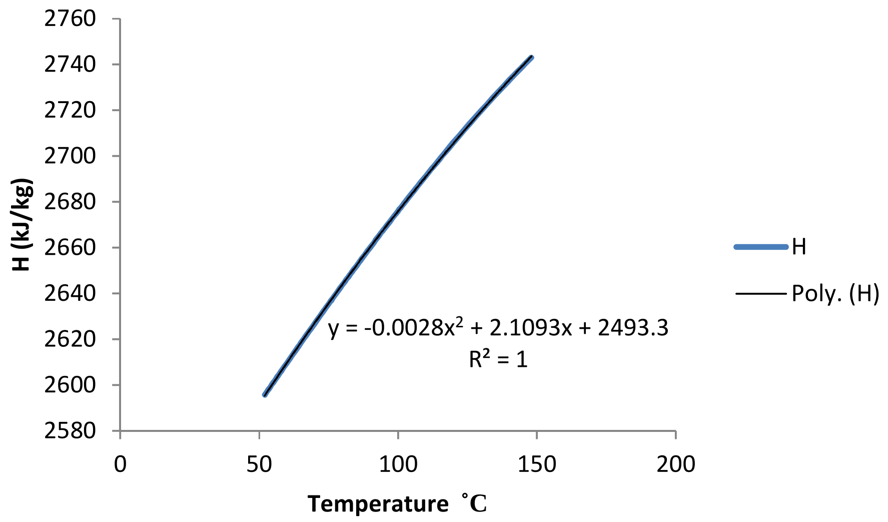

Figure. 4.3: Correlation for enthalpy of vapor

4.2 CORRELATION FOR PHYSICAL PROPERTIES AND BPR OF BLACK LIQUOR

For development of a mathematical model physico-thermal properties of black liquor are required. These properties are specific heat capacity of liquor, C_p and BPR, τ. In this work variation of BPR and specific heat of black liquor are calculated using Eqs. (4.4) and (4.5), respectively, as shown below.

Boiling point rise of the solutions can be estimated from (Bhargava et al., 2008)

$$\tau = 20\,(0.1 + x)^2 \qquad (4.5)$$

The heat capacity of the liquid solution is calculated from

$$C_P = C_1(1 - C_4 x) \qquad (4.6)$$

Where, values of coefficients C_1 and C_4 are 4.187 and 0.54, respectively (Bhargava et al., 2008).

4.3 MODEL FOR OVERALL HEAT TRANSFERCOEFFICIENT

The mathematical model of overall heat transfer coefficients of different effects is developed by Bhargava et al. (2008) based on plant data of seven effect evaporator system is shown in Eq. 4.7. The values of coefficients used in Eq.4.7 are shown in Table 1.

$$\frac{U_c}{2000} = a\left(\frac{\Delta T}{40}\right)^b \left(\frac{x_{avg}}{0.6}\right)^c \times \left(\frac{F_{avg}}{25}\right)^d \qquad (4.7)$$

Table 4.1: Value of Coefficients

Effect No.	a	b	c	d
1 and 2	0.0604	-0.3717	-1.2273	0.0748
3 to 7	0.1396	-0.7949	0.0	0.1673

4.4 MODEL DEVELOPMENT OF MEE SYSTEM

In the present section mathematical model is developed for seven effect system shown in Fig.3.1. The model is developed in different stages. The first stage considers the simple system with variation in physical properties, BPR and steam splitting. Further, this model is modified considering condensate flashing. Finally, the model is improved to include vapor bleeding from effects to use it in liquor preheating.

4.4.1 Simple model for the seven effect backward flow sequence evaporator system

The schematic diagram of a seven effect backward feed system selected for the development of simple model is presented in Figure 4.4. In the backward operation raw feed enters the last (coldest) effect and product is withdrawn from the first effect.In this system, live steam of amount, V_0, enters the steam chest of first effect at temperature T_0 and exits it as a condensate. The vapor generated in first effect, as a result of evaporation of liquor, is moved to the vapor chest of the second effect and so on. As a consequence of it, the first effect operates at the highest pressure (or highest temperature) whereas, last effect operates at lowest absolute pressure (or lowest temperature). The feed follows the backward sequence i.e. it first enters into the seventh effect and then moves to sixth, then to fifth, then to fourth and so on. This process continues till the liquor reaches to first effect from where it comes out as product.

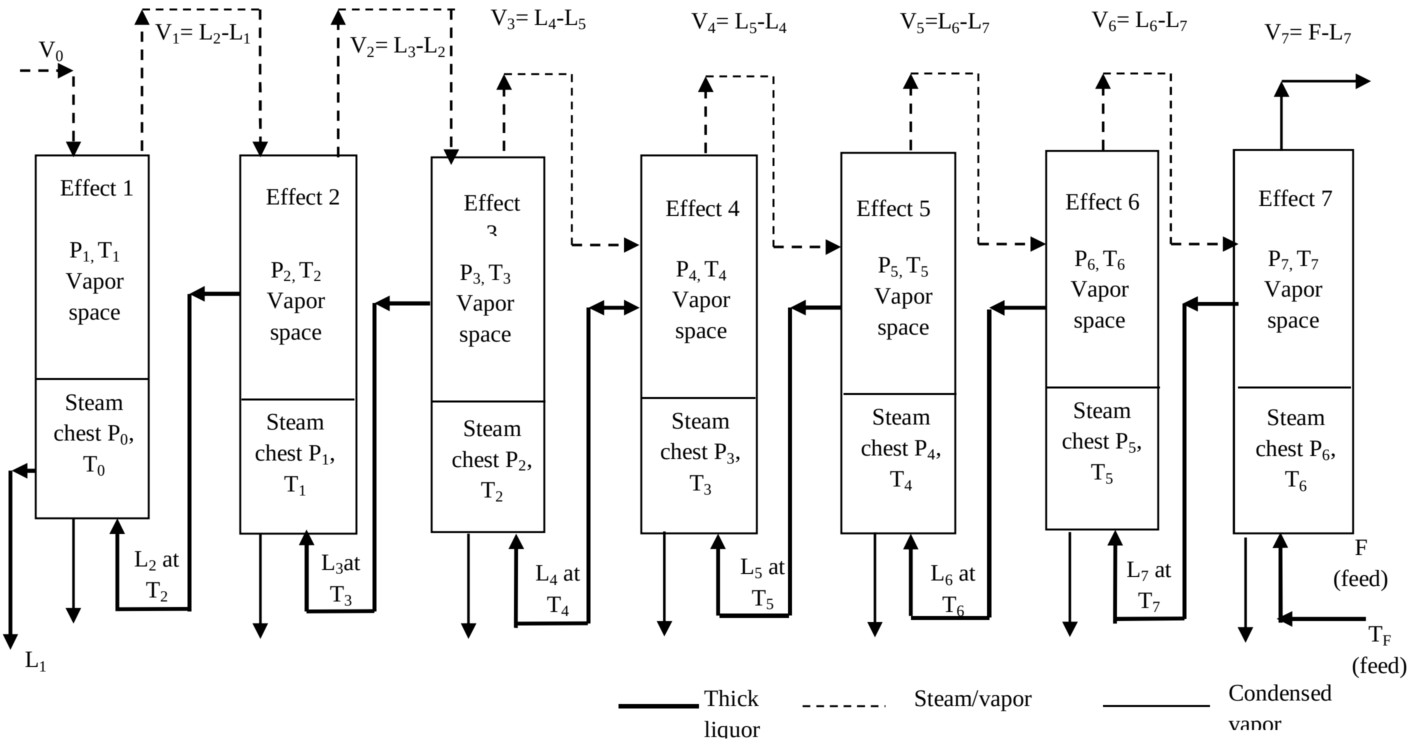

Figure 4.4: Seven effect evaporator system with back ward feed

To develop model for this system energy and material balances around first effect are described below:

Energy balance

[liquor entering the effect from its previous effect with sensible heat] + [steam entering the vapour chest with latent heat] = [vapour leaving the effect with latent heat] + [liquor leaving the effect with sensible heat]

$$[L_2 C_p T_2] + [V_0 \lambda_0] = [V_1 (h_1 + \lambda_1)] + [L_1 C_p T_1]$$

$$[L_2 C_p T_2] + [V_0 \lambda_0] = [V_1 h_1] + [V_1 \lambda_1] + [L_1 C_p T_1]$$

As $V_1 = L_2 - L_1$

$$[L_2 C_p T_2] + [V_0 \lambda_0] = [(L_2 - L_1) h_1] + [(L_2 - L_1) \lambda_1] + [L_1 C_p T_1]$$

Enthalpy, $h_1 = C_p T_1$

$$\left[L_2C_pT_2\right] + [V_0\lambda_0] = \left[(L_2 - L_1)C_pT_1\right] + [(L_2 - L_1)\lambda_1] + \left[L_1C_pT_1\right]$$

$$\left[L_2C_pT_2\right] + [V_0\lambda_0] = \left[\left(L_2C_pT_1\right) - \left(L_1C_pT_1\right)\right] + [(L_2 - L_1)\lambda_1] + \left[L_1C_pT_1\right]$$

Eliminating and reducing the terms, the equation finally becomes:

$$\left[L_2C_pT_2\right] + [V_0\lambda_0] = \left[L_2C_pT_1\right] + [(L_2 - L_1)\lambda_1]$$

Which is rearranged as:

$$\left[L_2C_p(T_2 - T_1)\right] + [V_0\lambda_0] - [(L_2 - L_1)\lambda_1] = 0$$

Hence the equations for the first effect are:

$$f_1 = \left[L_2C_p(T_2 - T_1)\right] + [V_0\lambda_0] - [(L_2 - L_1)\lambda_1] \tag{4.8}$$

Heat transferred to the effect = latent heat supplied by the steam

$$U_1A_1(T_0 - T_1) = V_0\lambda_0 \tag{4.9}$$

2nd effect

$$f_3 = \left[L_3C_p(T_3 - T_2)\right] + [(L_2 - L_1)\lambda_1] - [(L_3 - L_2)\lambda_2] \tag{4.10}$$

$$f_4 = U_2A_2(T_1 - T_2) - (L_2 - L_1)\lambda_1 \tag{4.11}$$

3rd effect

$$f_5 = \left[L_4C_p(T_4 - T_3)\right] + [(L_3 - L_2)\lambda_2] - [(L_4 - L_3)\lambda_3] \tag{4.12}$$

$$f_6 = U_3A_3(T_2 - T_3) - (L_3 - L_2)\lambda_2 \tag{4.13}$$

4th effect

$$f_7 = \left[L_5C_p(T_5 - T_4)\right] + [(L_4 - L_3)\lambda_3] - [(L_5 - L_4)\lambda_4] \tag{4.14}$$

$$f_8 = U_4A_4(T_3 - T_4) - (L_4 - L_3)\lambda_3 \tag{4.15}$$

5th effect

$$f_9 = \left[L_6 C_p (T_6 - T_5)\right] + \left[(L_5 - L_4)\lambda_4\right] - \left[(L_6 - L_5)\lambda_5\right] \tag{4.16}$$

$$f_{10} = U_5 A_5 (T_4 - T_5) - (L_5 - L_4)\lambda_4 \tag{4.17}$$

6^{th} effect

$$f_{11} = \left[L_7 C_p (T_7 - T_6)\right] + \left[(L_6 - L_5)\lambda_5\right] - \left[(L_7 - L_6)\lambda_6\right] \tag{4.18}$$

$$f_{12} = U_6 A_6 (T_5 - T_6) - (L_6 - L_5)\lambda_5 \tag{4.19}$$

7^{th} effect

For the last effect where the feed enters, the liquor flow rate is replaced by the entering feed flow rate F and temperature of feed T_f

$$f_{13} = \left[F C_p \left(T_f - T_7\right)\right] + \left[(L_7 - L_6)\lambda_6\right] - \left[(F - L_7)\lambda_7\right] \tag{4.20}$$

$$f_{14} = U_7 A_7 (T_6 - T_7) - (L_7 - L_6)\lambda_6 \tag{4.21}$$

Thus, total fourteen equations are derived for the model of simple system, shown in Fig. 4.4.

4.4.2 Model with variation in physical properties, BPR and steam splitting

The actual MEE system cannot be simulated without considering variation in physical properties. These properties are specific heat capacity of liquor, C_p, latent heat of vaporization, λ, and BPR. Using all variations of physical properties model of seven effect evaporator system is developed. In this system steam is split equally among first and second effects as shown in Fig. 4.5. The assumptions are as follows: vapor leaving from both the effect is entering to steam chest of third effect. Heat loss from effect is negligible.

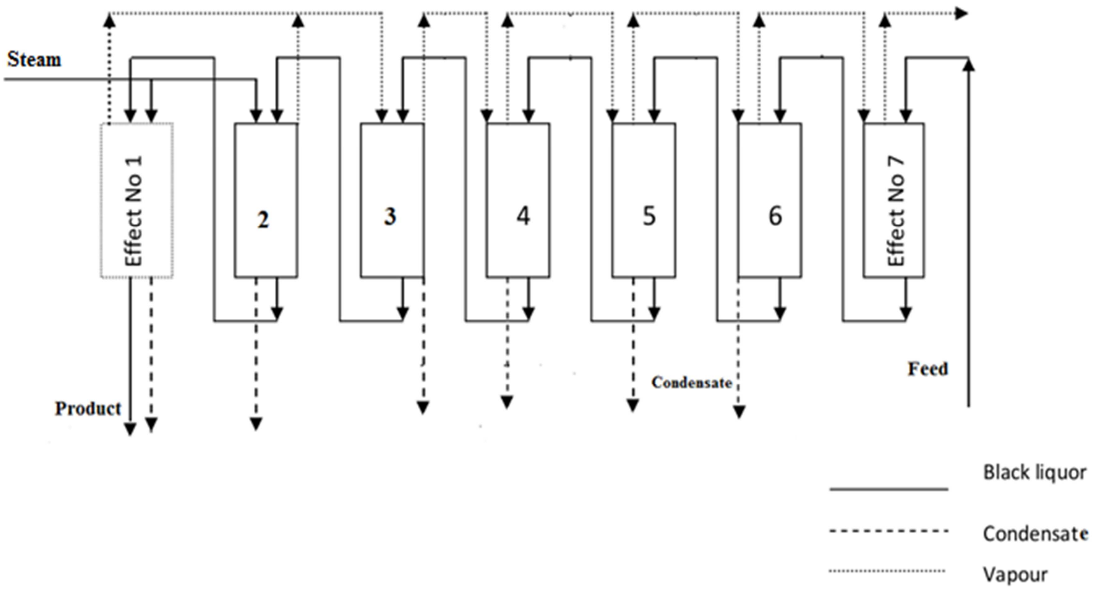

Figure 4.5: Seven effect evaporator system with steam splitting

Equations for first to seventh effects are formulated based on material and energy balances as derived Eq. 4.8 and shown below:

1st effect

$$f_1 = \left[L_2 C_{p2}(T_2 + \tau_2)\right] + [0.5V_{01}\lambda_{01}] - \left[L_1 C_{p1}(T_1 + \tau_1)\right] - \left[(L_2 - L_1)\left(\lambda_1 + (4.2T_1)\right)\right] \tag{4.22}$$

$$f_2 = U_1 A_1(T_{01} - T_1 - \tau_1) - (0.5V_{01}\lambda_{01}) \tag{4.23}$$

2nd effect

$$f_3 = \left[L_3 C_{p3}(T_3 + tou_3)\right] + [0.5V_{02}\lambda_{02}] - \left[L_2 C_{p2}(T_2 + \tau_2)\right] - \left[(L_3 - L_2)\left(\lambda_2 + (4.2T_2)\right)\right] \tag{4.24}$$

$$f_4 = U_2 A_2(T_{02} - T_2 - \tau_2) - [0.5V_{02}\lambda_{02}] \tag{4.25}$$

3rd effect

$$f_5 = \left[L_4 C_{p4}(T_4 + \tau_4)\right] - \left[L_3 C_{p3}(T_3 + \tau_3)\right] + (L_2 - L_1)\lambda_1 + (L_3 - L_2)\lambda_2 - \left[(L_4 - L_3)\left(\lambda_3 + (4.2T_3)\right)\right] \tag{4.26}$$

$$f_6 = U_3 A_3 \left(\frac{T_1+T_2}{2} - \mathrm{T}_3 - \tau_3\right) - (\mathrm{L}_2 - \mathrm{L}_1)\lambda_1 - (\mathrm{L}_3 - \mathrm{L}_2)\lambda_2 \tag{4.27}$$

4th effect

$$f_7 = \left[\mathrm{L}_5\mathrm{C}_{\mathrm{p}5}(\mathrm{T}_5 + \tau_5)\right] - \left[\mathrm{L}_4\mathrm{C}_{\mathrm{p}4}(\mathrm{T}_4 + \tau_4)\right] + (\mathrm{L}_4 - \mathrm{L}_3)\lambda_3 - \left[(\mathrm{L}_5 - \mathrm{L}_4)\left(\lambda_4 + (4.2\mathrm{T}_4)\right)\right] \tag{4.28}$$

$$f_8 = U_4 A_4(\mathrm{T}_3 - \mathrm{T}_4 - \tau_4) - \left[(\mathrm{L}_4 - \mathrm{L}_3)\lambda_3\right] \tag{4.29}$$

5th effect

$$f_9 = \left[\mathrm{L}_6\mathrm{C}_{\mathrm{p}6}(\mathrm{T}_6 + \tau_6)\right] - \left[\mathrm{L}_5\mathrm{C}_{\mathrm{p}5}(\mathrm{T}_5 + \tau_5)\right] + (\mathrm{L}_5 - \mathrm{L}_4)\lambda_4 - \left[(\mathrm{L}_6 - \mathrm{L}_5)\left(\lambda_5 + (4.2\mathrm{T}_5)\right)\right] \tag{4.30}$$

$$f_{10} = U_5 A_5(\mathrm{T}_4 - \mathrm{T}_5 - \tau_5) - \left[(\mathrm{L}_5 - \mathrm{L}_4)\lambda_4\right] \tag{4.31}$$

6th effect

$$f_{11} = \left[\mathrm{L}_7\mathrm{C}_{\mathrm{p}7}(\mathrm{T}_7 + \tau_7)\right] - \left[\mathrm{L}_6\mathrm{C}_{\mathrm{p}6}(\mathrm{T}_6 + \tau_6)\right] + (\mathrm{L}_6 - \mathrm{L}_5)\lambda_5 - \left[(\mathrm{L}_7 - \mathrm{L}_6)\left(\lambda_6 + (4.2\mathrm{T}_6)\right)\right] \tag{4.32}$$

$$f_{12} = U_6 A_6(\mathrm{T}_5 - \mathrm{T}_6 - \tau_6) - \left[(\mathrm{L}_6 - \mathrm{L}_5)\lambda_5\right] \tag{4.33}$$

7th effect

$$f_{13} = \left[\mathrm{FC}_{\mathrm{pf}}\mathrm{T}_f\right] - \left[\mathrm{L}_7\mathrm{C}_{\mathrm{p}7}(\mathrm{T}_7 + \tau_7)\right] + (\mathrm{L}_7 - \mathrm{L}_6)\lambda_6 - \left[(\mathrm{F} - \mathrm{L}_7)(\lambda_7 + (4.2T_7))\right] \tag{4.34}$$

$$f_{14} = U_7 \times A_7 \times (\mathrm{T}_6 - \mathrm{T}_7 - \tau_7) - \left[(\mathrm{L}_7 - \mathrm{L}_6)\lambda_6\right] \tag{4.35}$$

4.4.3 Model with condensate flashing

The condensate (water in present case), which exits from steam/vapor chest of an effect, contains sufficient amount of sensible heat which can be put to use. This sensible heat can be extracted by means of flashing which will produce low pressure vapor. This vapor can be used as a heating medium in vapor chests of appropriate effects and thereby can improve steam economy of the whole system. In this section along with variation in physical properties condensate flashing is also included in the model. The schematic diagram of this system is shown in Figure 4.6.

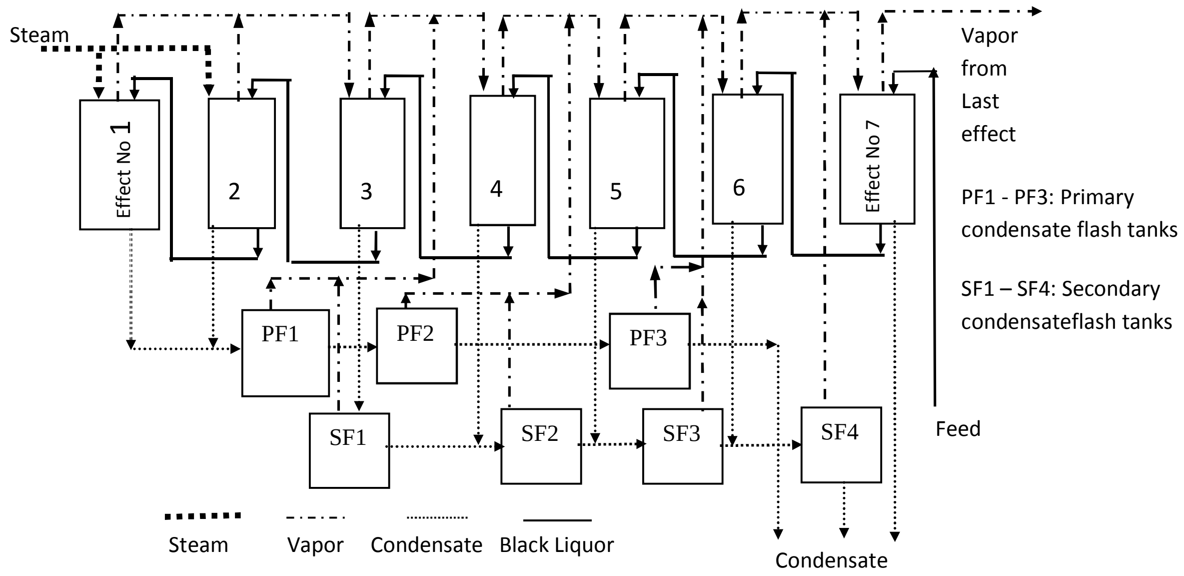

Figure 4.6 Seven effect evaporator system with condensate flashing

The amount of vapor generated through flashing can be computed based on material and energy balance around a flash tank shown in Figure 4.7. Here V_0 is amount of vapour entering the first primary flash tank PF1 at T_0 which is flashed at T_3. V_{0v} is the amount of vapour leaving the flash tank at temperature T_1 and V_{0L} is the condensate leaving the flash tank that is led to the second flash tank for flashing at T_1. The expression of V_{0v} can be derived as given below:

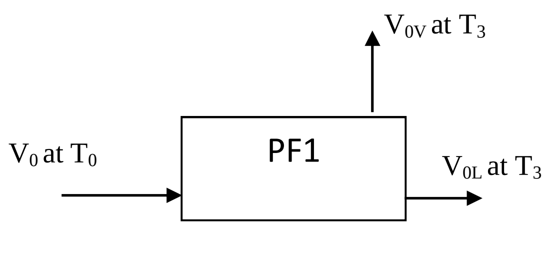

Figure 4.7: Schematic diagram of primary condensate flash tank PF1

Material balance around PF1:$V_0 = V_{0v} + V_{0L}$

Energy balance around PF1: $V_0 h_0 = V_{0v} H_{0v} + V_{0L} h_{0L}$

Solving above equations,

$$V_{0v} = V_0 \left[\frac{(h_0 - h_{0L})}{(H_{0v} - h_{0L})}\right]$$

The values of h_0, h_{0L} and H_{0v} are computed at temperature T_0 and T_1.

Assuming $\left[\frac{(h_0 - h_{0L})}{(H_{0v} - h_{0L})}\right] = PF_1$

$$V_{0v} = V_0 PF_1$$

$$V_{0L} = V_0 \left[1 - \frac{(h_0 - h_{0L})}{(H_{0v} - h_{0L})}\right]$$

$$V_{0L} = V_0 [1 - PF_1]$$

Similarly for SF1

$$V_{1V} = V_1 \left[\frac{(h_1 - h_{1L})}{(H_{1v} - h_{1L})}\right]$$

Assuming $\left[\frac{(h_1 - h_{1L})}{(H_{1v} - h_{1L})}\right] = SF_1$

As the vapor generated through flashing is entering into vapor chest of fourth to seventh effects the governing equation for these effect will be modified. Thus, for first to third effects the equations are similar to previous equations 4.22 to 4.27. The equations for fourth to seventh effects are derived based on mass and energy balance around the system.

The equation for fourth effect is derived based on mass and energy balance around the system, shown in Figure 4.8 as given below:

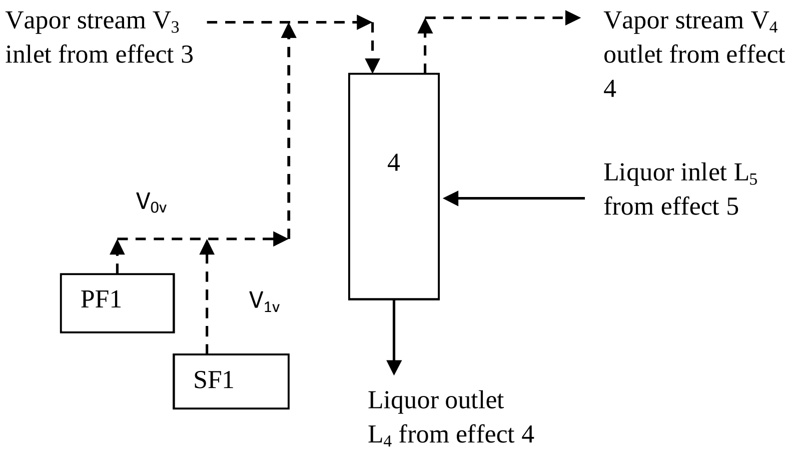

Figure 4.8 Material and energy balance around 4^{th} effect with flashing

Energy Balance around 4^{th} effect gives:

[Sensible heat of liquor (L_5)]+ [latent heat of vapour (V_3)] +

[latent heat of vapour streams from PF1 and SF1 (V_{0v}+V_{1v})] = [Sensible heat of liquor (L_4)] + [latent heat of vapor stream (V_4)]

$$f_7 = \left[\mathrm{L_5 C_{p5}(T_5 + \tau_5)}\right] - \left[\mathrm{L_4 C_{p4}(T_4 + \tau_4)}\right] + \left((\mathrm{L_4} - \mathrm{L_3}) + V_{0V} + V_{1V}\right)\lambda_3 - \left[(\mathrm{L_5} - \mathrm{L_4})\left(\lambda_4 + (4.2\mathrm{T_4})\right)\right] \tag{4.36}$$

$$f_8 = U_4 A_4(\mathrm{T_3} - \mathrm{T_4} - \tau_4) - \left((\mathrm{L_4} - \mathrm{L_3}) + V_{0V} + V_{1V}\right)\lambda_3 \tag{4.37}$$

5^{th} effect

$$f_9 = \left[\mathrm{L_6 C_{p6}(T_6 + \tau_6)}\right] - \left[\mathrm{L_5 C_{p5}(T_5 + \tau_5)}\right] + [(\mathrm{L_5} - \mathrm{L_4}) + \mathrm{V_{0LV1}} + \mathrm{V_V'}]\lambda_4 - \left[(\mathrm{L_6} - \mathrm{L_5})\left(\lambda_5 + (4.2 \times \mathrm{T_5})\right)\right] \tag{4.38}$$

$$f_{10} = U_5 A_5(\mathrm{T_4} - \mathrm{T_5} - \tau_5) - [(\mathrm{L_5} - \mathrm{L_4}) + \mathrm{V_{0LV1}} + \mathrm{V_V'}]\lambda_4 \tag{4.39}$$

6th effect

$$f_{11} = \left[\mathrm{L_7 C_{p7}(T_7 + \tau_7)}\right] - \left[\mathrm{L_6 C_{p6}(T_6 + \tau_6)}\right] + [(\mathrm{L_6 - L_5}) + \mathrm{V_{0LV2}} + \mathrm{V'_{1V}}]\lambda_5 - \left[(\mathrm{L_7 - L_6})\left(\lambda_6 + (4.2\mathrm{T_6})\right)\right] \quad (4.40)$$

$$f_{12} = U_6 A_6(\mathrm{T_5 - T_6 - \tau_6}) - [(\mathrm{L_6 - L_5}) + \mathrm{V_{0LV2}} + \mathrm{V'_{1V}}]\lambda_5 \quad (4.41)$$

7th effect

$$f_{13} = \left[\mathrm{FC_{pf}T}_f\right] - \left[\mathrm{L_7 C_{p7}(T_7 + \tau_7)}\right] + [(\mathrm{L_7 - L_6}) + \mathrm{V_{0LV3}} + \mathrm{V'_{2V}}]\lambda_6 - \left[(\mathrm{F - L_7})\left(\lambda_7 + (4.2 \times T_7)\right)\right] \quad (4.42)$$

$$f_{14} = U_7 \times A_7 \times (\mathrm{T_6 - T_7 - \tau_7}) - [(\mathrm{L_7 - L_6}) + \mathrm{V_{0LV3}} + \mathrm{V'_{2V}}]\lambda_6 \quad (4.43)$$

4.4.4 Model with vapor bleeding

Vapor bleeding is done so as to pre heat the liquor that is coming out from one effect with a part of stream of vapor extracted from the stream entering as a heating medium to one of the effects. As shown in the Figure 4.9, there are four pre heaters placed in between 3rdand 4th effect and so on till 7th effect. The vapor 'bled' or extracted from the vapor coming out from 2nd effect is used to pre heat the liquor that is coming from the 4th effect (before it enters the 3rd effect) with a pre heater placed in between 3rd and the 4th effect. Others are placed consecutively. The material and energy balance equations are derived around each effect and additionally done for each pre heater as well.

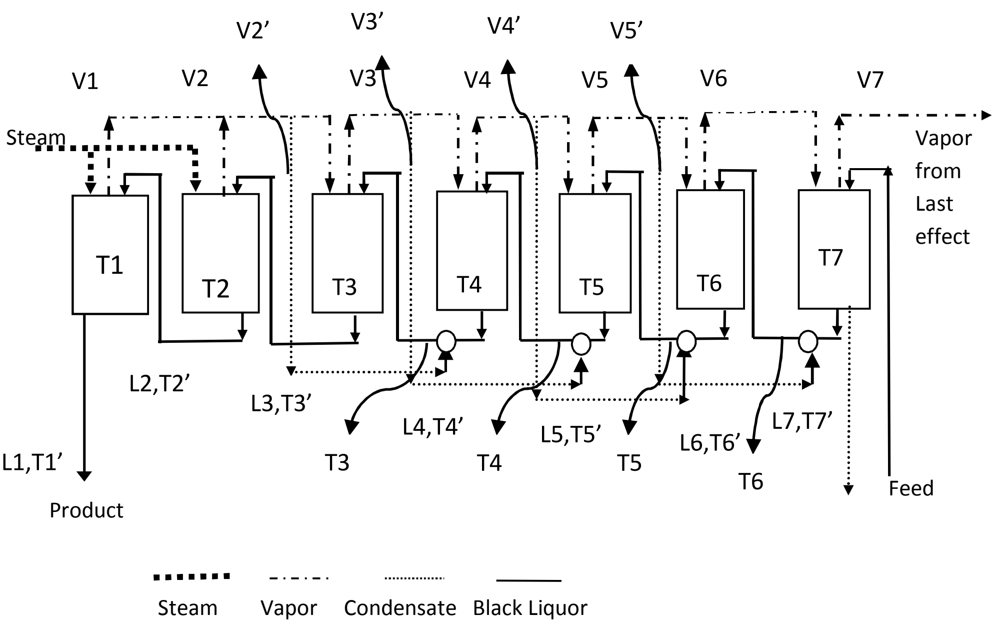

Figure 4.9: Schematic diagram of seven effect system with vapor bleeding

Two configurations of vapor bleeding are considered in the present work. In both cases four pre heaters are placed between effects 3 and 7.In case of first configuration (configuration 1), the vapor required for pre heaters placed between 3^{rd} and 4^{th}, 4^{th} and 5^{th}, 5^{th} and $6^{th}$and 6^{th} and 7^{th} effects are bled from V_2, V_3, V_4,and V_5, respectively which is shown in figure 4.9.

The schematic diagram of pre heater-1which is in between effects 3 & 4 is shown in Figure 4.10.

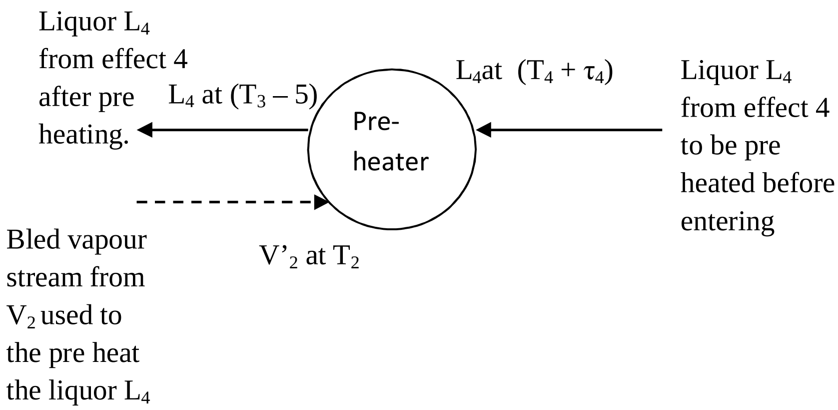

Figure 4.10 Schematic diagram of pre-heater 1

Material balance around pre- heater 1 is given as:

$$V_2'\lambda_2 = L_4C_{p4}(T_3 - 5 - T_4 - \tau_4)$$

Equations of 3rd effect can be developed using Figure 4.11:

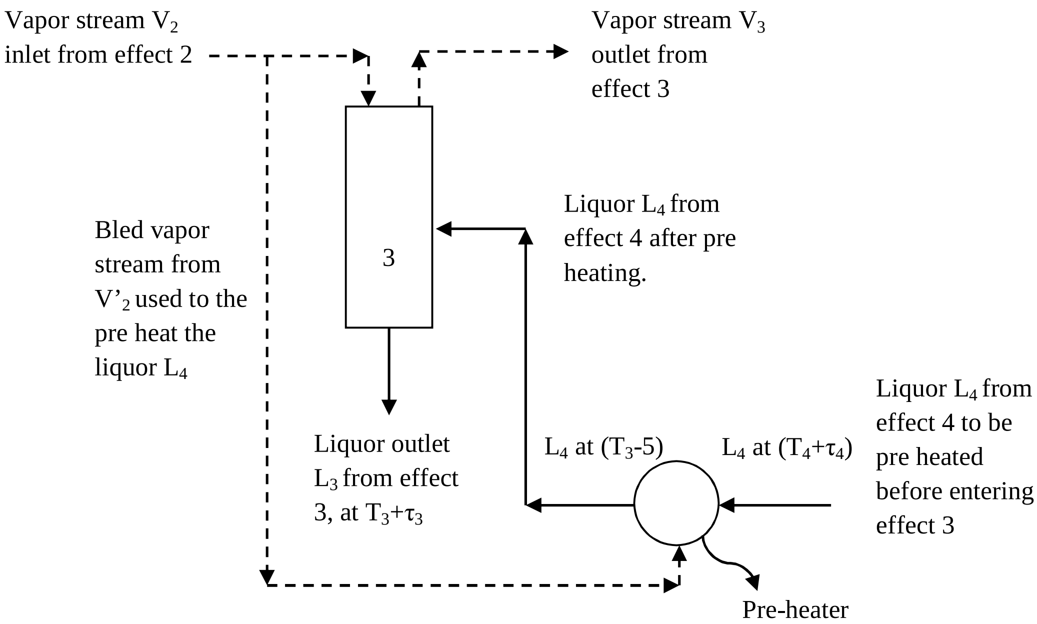

Figure 4.11 Schematic diagram of 3rd effect with vapor bleeding

Equations for 1st, 2nd and 7th effect will similar to that of previous model mentioned in section 4.4.2. For rest of the effects equations are developed as given described below.
Energy balance around 3rd effect is given as

[Sensible heat of liquor (L_4)]+ [latent heat of vapour (V_1)] + [latent heat of vapour (V_2)] – [Latent heat of vapor (V'_2)] = [Sensible heat of liquor (L_3)] + [latent heat of vapor stream (V_3)]

3rd effect

$$f_5 = \left[\mathrm{L_4 C_{p4}}(T_3 - 5)\right] - \left[\mathrm{L_3 C_{p3}}(\mathrm{T_3} + \tau_3)\right] + (\mathrm{L_2} - \mathrm{L_1})\lambda_1 + (\mathrm{L_3} - \mathrm{L_2})\lambda_2 - V_2'\lambda_2 - \left[(\mathrm{L_4} - \mathrm{L_3})\left(\lambda_3 + (4.2\mathrm{T_3})\right)\right] \quad (4.44)$$

$$f_6 = U_3 A_3 \left(\frac{T_1+T_2}{2} - \mathrm{T_3} - \tau_3\right) - (\mathrm{L_2} - \mathrm{L_1})\lambda_1 - (\mathrm{L_3} - \mathrm{L_2})\lambda_2 - V_2'\lambda_2 \quad (4.45)$$

$$f_7 = V_2'\lambda_2 - L_4 C_{p4}(T_3 - 5 - T_4 - \tau_4) \quad (4.46)$$

4^{th} effect

$$f_8 = \left[\mathrm{L_5 C_{p5}}(T_4 - 5)\right] - \left[\mathrm{L_4 C_{p4}}(\mathrm{T_4} + \tau_4)\right] + (\mathrm{L_4} - \mathrm{L_3} - V_3')\lambda_3 - \left[(\mathrm{L_5} - \mathrm{L_4})\big(\lambda_4 + (4.2\mathrm{T_4})\big)\right] \quad (4.47)$$

$$f_9 = U_4 A_4(\mathrm{T_3} - \mathrm{T_4} - \tau_4) - \left[(\mathrm{L_4} - \mathrm{L_3} - V_3')\lambda_3\right] \quad (4.48)$$

$$f_{10} = V_3'\lambda_3 - L_5 C_{p5}(T_4 - 5 - T_5 - \tau_5) \quad (4.49)$$

5^{th} effect

$$f_{11} = \left[\mathrm{L_6 C_{p6}}(T_5 - 5)\right] - \left[\mathrm{L_5 C_{p5}}(\mathrm{T_5} + \tau_5)\right] + (\mathrm{L_5} - \mathrm{L_4} - V_4')\lambda_4 - \left[(\mathrm{L_6} - \mathrm{L_5})\big(\lambda_5 + (4.2 \times \mathrm{T_5})\big)\right] \quad (4.50)$$

$$f_{12} = U_5 A_5(\mathrm{T_4} - \mathrm{T_5} - \tau_5) - \left[(\mathrm{L_5} - \mathrm{L_4} - V_4')\lambda_4\right] (4.46)$$

$$f_{13} = V_4'\lambda_4 - L_6 C_{p6}(T_5 - 5 - T_6 - \tau_6) \quad (4.51)$$

6^{th} effect

$$f_{14} = \left[\mathrm{L_7 C_{p7}}(T_6 - 5)\right] - \left[\mathrm{L_6 C_{p6}}(\mathrm{T_6} + \tau_6)\right] + (\mathrm{L_6} - \mathrm{L_5} - V_5')\lambda_5 - \left[(\mathrm{L_7} - \mathrm{L_6})\big(\lambda_6 + (4.2\mathrm{T_6})\big)\right] \quad (4.52)$$

$$f_{15} = U_6 A_6(\mathrm{T_5} - \mathrm{T_6} - \lambda_6) - \left[(\mathrm{L_6} - \mathrm{L_5} - V_5')\lambda_5\right] \quad (4.53)$$

$$f_{16} = V_5'\lambda_5 - L_7 C_{p7}(T_6 - 5 - T_7 - \tau_7) \quad (4.54)$$

In second configuration(configuration 2), the vapor required for pre heaters placed between 3^{rd} and 4^{th}, 4^{th} and 5^{th}, 5^{th} and $6^{th}$and 6^{th} and 7^{th} effects are bled from V_3, V_4, V_5,and V_6, respectively. Here liquor is preheated up to average temperature of both the effect between them preheater placed. This can be explained by taking the example of preheater placed in between 3^{rd} and 4^{th} effects. The liquor stream L_4 coming out from 4^{th} effect is pre-heated before it enters 3^{rd} effect using part of vapor that is bled from the vapour stream entering the 4^{th} effect. So, the liquor L_4 which has to attain a temperature of $(T_3+T_4)/2$ from T_3, is already achieving an intermediate temperature between T_3 and T_4 before it enters the 3^{rd} effect.

4.4.5 Model with vapour bleeding and flashing

This model is the summation of all the variations considered so far. It includes steam splitting, variation in physical properties, vapor bleeding and condensate flashing together. The portion of vapor that enter to the next effect is bled to preheat the liquor entering the following effect and also added up with the flashed vapor from the flash tank before entering the steam chest for heating the next effect.

The variation can be shown by performing material and energy balance around 4th effect which has a pre-heater to heat liquor coming out from it before it enters the 3rd effect and vapour streams which has the streams V_{0v}, V_{1v}, combined with V_3 entering into the steam chest as shown in Figure 4.12.

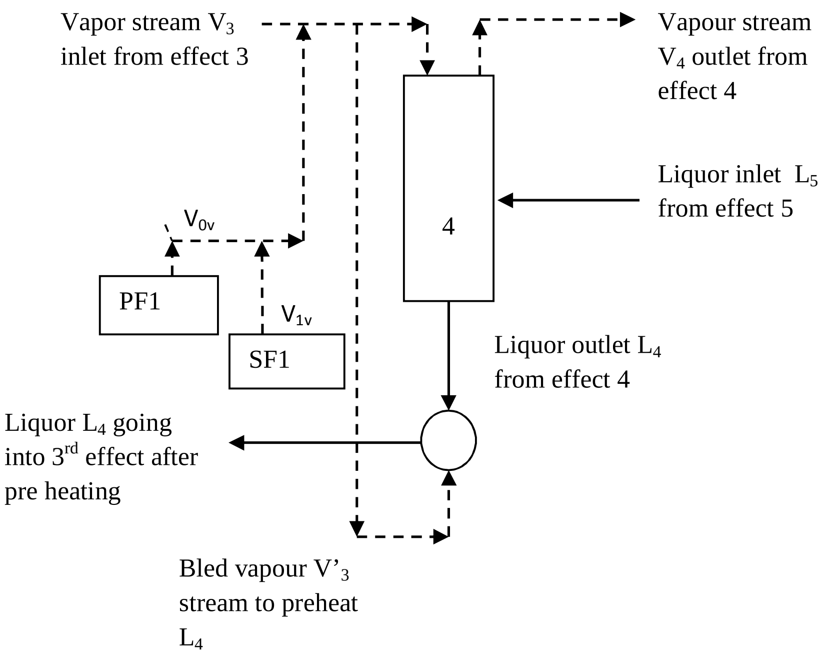

Figure 4.12 Schematic diagram of 4th effect with vapor bleeding and flashing

Energy balance around 4th effect is given as

[Sensible heat of liquor (L_5)]+ [latent heat of vapour (V_3)] – [Latent heat of vapor(V'_2)] +

[latent heat of vapour streams from PF1 and SF1 (V_{0v}+V_{1v})] = [Sensible heat of liquor (L_4)] + [latent heat of vapor stream (V_4)]

3rd effect

$$f_5 = \left[L_4 C_{p4}\left(\frac{T_3+T_4}{2}\right)\right] - \left[L_3 C_{p3}(T_3+\tau_3)\right] + (L_2 - L_1)\lambda_1 + (L_3 - L_2)\lambda_2 - \left[(L_4 - L_3)\left(\lambda_3 + (4.2T_3)\right)\right] \quad (4.55)$$

$$f_6 = U_3 A_3\left(\frac{T_1+T_2}{2} - T_3 - \tau_3\right) - (L_2 - L_1)\lambda_1 - (L_3 - L_2)\lambda_2 \quad (4.56)$$

$$f_7 = V_3'\lambda_3 - L_4 C_{p4}\left(\frac{T_3+T_4}{2} - T_4 - \tau_4\right) \quad (4.57)$$

4th effect

$$f_8 = \left[L_5 C_{p5}\left(\frac{T_4+T_5}{2}\right)\right] - \left[L_4 C_{p4}(T_4+\tau_4)\right] + \left((L_4 - L_3) + V_{0V} + V_{1V} - V_3'\right)\lambda_3 - \left[(L_5 - L_4)\left(\lambda_4 + (4.2T_4)\right)\right] \quad (4.58)$$

$$f_9 = U_4 A_4(T_3 - T_4 - \tau_4) - \left((L_4 - L_3) + V_{0V} + V_{1V} - V_3'\right)\lambda_3 \quad (4.59)$$

$$f_{10} = V_4'\lambda_4 - L_5 C_{p5}\left(\frac{T_4+T_5}{2} - T_5 - \tau_5\right) \quad (4.60)$$

5th effect

$$f_{11} = \left[L_6 C_{p6}\left(\frac{T_5+T_6}{2}\right)\right] - \left[L_5 C_{p5}(T_5+\tau_5)\right] + [(L_5 - L_4) - V_4']\lambda_4 - \left[(L_6 - L_5)\left(\lambda_5 + (4.2\times T_5)\right)\right] \quad (4.61)$$

$$f_{12} = U_5 A_5(T_4 - T_5 - \tau_5) - [(L_5 - L_4) - V_4']\lambda_4 \quad (4.62)$$

$$f_{13} = V_5'\lambda_5 - L_6 C_{p6}\left(\frac{T_5+T_6}{2} - T_6 - \tau_6\right) \quad (4.63)$$

6th effect

$$f_{14} = \left[L_7 C_{p7}\left(\frac{T_6+T_7}{2}\right)\right] - \left[L_6 C_{p6}(T_6+\tau_6)\right] + [(L_6 - L_5) + V_{0LV1} + V_{2V} - V_5']\lambda_5 - \left[(L_7 - L_6)\left(\lambda_6 + (4.2T_6)\right)\right] \quad (4.64)$$

$$f_{15} = U_6 A_6(T_5 - T_6 - \tau_6) - [(L_6 - L_5) + V_{0LV1} + V_{2V} - V_5']\lambda_5 \quad (4.65)$$

$$f_{16} = V_6'\lambda_6 - L_7 C_{p7}\left(\frac{T_7+T_6}{2} - T_7 - \tau_7\right) \quad (4.66)$$

7th effect

$$f_{17} = [\mathrm{FC_{pf}T}_f] - [\mathrm{L_7C_{p7}(T_7 + \tau_7)}] + [(\mathrm{L_7 - L_6}) + \mathrm{V_{3V}} - V_6']\lambda_6 - [(\mathrm{F - L_7})(\lambda_7 + (4.2 \times T_7))] \quad (4.67)$$

$$f_{18} = U_7 \times A_7 \times (\mathrm{T_6 - T_7 - \tau_7}) - [(\mathrm{L_7 - L_6}) + \mathrm{V_{3V}} - V_6']\lambda_6 \quad (4.68)$$

4.4.6 Model for preheating of liquor using condensate

Further, a new model is developed where condensate of an effect is used to preheat the liquor, which is entering into that effect using a counter current heat exchanger. The modified seven effect evaporator system is shown in Figure 4.13 in which four heat exchangers (preheaters) are used to preheat the liquor. Here condensate is employed as a heating medium instead of bled vapor. Figure 4.13 shows that condensates of live steams, C_{01} and C_{02} are utilized in the process to preheat the liquor coming from the forth effect. Condensates of vapor chest of third, fourth and fifth effect are utilized to preheat the liquor coming from the fifth, sixth and seventh effect respectively. In this model liquor enters into the effect at effect's temperature otherwise near to its value.

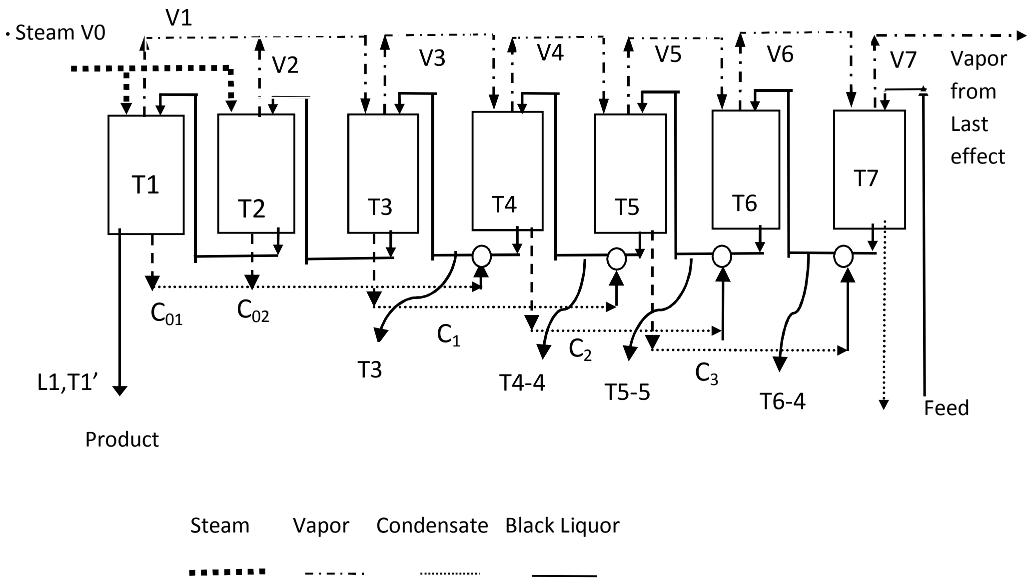

Figure 4.13 Schematic diagram of seven effect system preheating of liquor using condensate

Equations of 3rd effect can be developed using Figure 4.14:

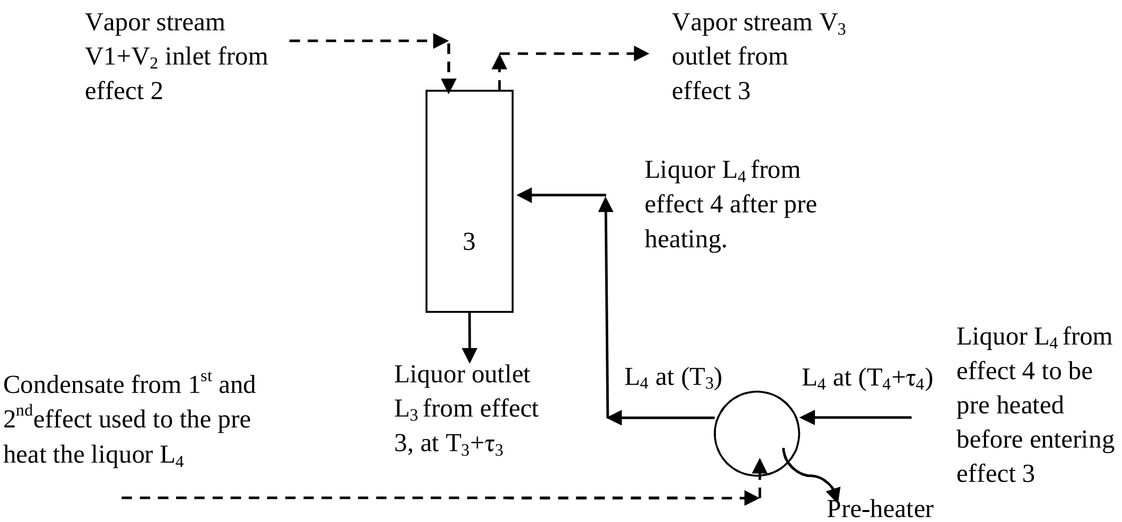

Figure 4.14 Schematic diagram of 3rd effect with preheating using condensate

Equations for 1st, 2nd and 7th effect will similar to that of previous Eqs 4.22 to 4.25 and 4.34 to 4.35 mentioned in section 4.4.2. For rest of the effects equations are developed as given described below.

Energy balance around 3rd effect is given as

[Sensible heat of liquor (L_4)]+ [latent heat of vapour (V_1)] + [latent heat of vapour (V_2)] = [Sensible heat of liquor (L_3)] + [latent heat of vapor stream (V_3)]

3rd effect

$$f_5 = \left[L_4 C_{p4} T_3\right] - \left[L_3 C_{p3}(T_3 + \tau_3)\right] + (L_2 - L_1)\lambda_1 + (L_3 - L_2)\lambda_2 - \left[(L_4 - L_3)\left(\lambda_3 + (4.2T_3)\right)\right] \tag{4.69}$$

$$f_6 = U_3 A_3 \left(\frac{T_1+T_2}{2} - T_3 - \tau_3\right) - (L_2 - L_1)\lambda_1 - (L_3 - L_2)\lambda_2 \tag{4.70}$$

4th effect

$$f_7 = \left[L_5 C_{p5}(T_4 - 4)\right] - \left[L_4 C_{p4}(T_4 + \tau_4)\right] + (L_4 - L_3)\lambda_3 - \left[(L_5 - L_4)\left(\lambda_4 + (4.2T_4)\right)\right] \tag{4.71}$$

$$f_8 = U_4 A_4(\mathrm{T}_3 - \mathrm{T}_4 - \tau_4) - [(\mathrm{L}_4 - \mathrm{L}_3)\lambda_3] \quad (4.72)$$

5th effect

$$f_9 = [\mathrm{L}_6 \mathrm{C}_{p6}(T_5 - 5)] - [\mathrm{L}_5 \mathrm{C}_{p5}(\mathrm{T}_5 + \tau_5)] + (\mathrm{L}_5 - \mathrm{L}_4)\lambda_4 - [(\mathrm{L}_6 - \mathrm{L}_5)(\lambda_5 + (4.2 \times \mathrm{T}_5))] \quad (4.73)$$

$$f_{10} = U_5 A_5(\mathrm{T}_4 - \mathrm{T}_5 - \tau_5) - [(\mathrm{L}_5 - \mathrm{L}_4)\lambda_4] \quad (4.74)$$

6th effect

$$f_{11} = [\mathrm{L}_7 \mathrm{C}_{p7}(T_6 - 4)] - [\mathrm{L}_6 \mathrm{C}_{p6}(\mathrm{T}_6 + \tau_6)] + (\mathrm{L}_6 - \mathrm{L}_5)\lambda_5 - [(\mathrm{L}_7 - \mathrm{L}_6)(\lambda_6 + (4.2\mathrm{T}_6))] \quad (4.75)$$

$$f_{12} = U_6 A_6(\mathrm{T}_5 - \mathrm{T}_6 - \lambda_6) - [(\mathrm{L}_6 - \mathrm{L}_5)\lambda_5] \quad (4.76)$$

Thus, in this chapter models with steam splitting, variation in physical properties, condensate flashing, vapor bleeding and preheating of liquor using condensate are developed.

CHAPTER 5

SOLUTION TECHNIQUES

CHAPTER 5

SOLUTION TECHNIQUES

This Chapter deals with the solutions techniques of mathematical models developed in Chapter 4 for the seven effects evaporator system operating at different conditions. The solution of these models requires an iterative approach as number of parameters such as variable physical properties, BPE, overall heat transfer coefficient, etc., are involved in the models which depend on unknown intermediate temperatures. The set of non-linear equations developed in chapter 4 is solved using Systems of Non-Linear Equations Software. A detailed algorithm explaining the series of steps performed for solution of developed models is given as follows:

Step 1: Values of known parameters are collected from Table 3.1.

Step 2: Equal temperature drop and equal vaporization in each effect are assumed initially to calculate temperatures and liquor flow rates for each effect. An initial guess of overall heat transfer coefficient for each effect is made to start the calculation.

Step 3: The overall component balance is used to determine the product stream flow rate. The component and material balance is used to get estimates for the flow rates and the compositions of the intermediate streams within the system.

Step 4: The compositions are used to estimate BPEs and specific heat of the solution. The temperature and composition estimated in Step 2 and 3 are used to get enthalpy values.

Step 5: The inclusion of variations such as steam splitting, variation in specific heat capacity, BPE, latent heat of vaporization, condensate flashing preheating of liquor using condensate and vapor bleeding are considered.

Step 6: Based on values of U set of nonlinear equations are developed which are solved to obtain the revised values of temperatures and liquor flow rate of each effect using solver 'system of nonlinear equations'.

Step 7: Revised values of U are computed considering temperature, flow rate and concentration of each effect.

Step 8: Revised values of U are compared with the previous iteration values. If difference of U is not within $\pm 40\%$ the calculation from Step 3 to 10 are repeated with revised values of temperature, liquor flow rates and U until the system converges.

Step 9: Steam economy is computed.

Algorithm explaining the series of steps performed for final solution is shown in Fig. 5.1.

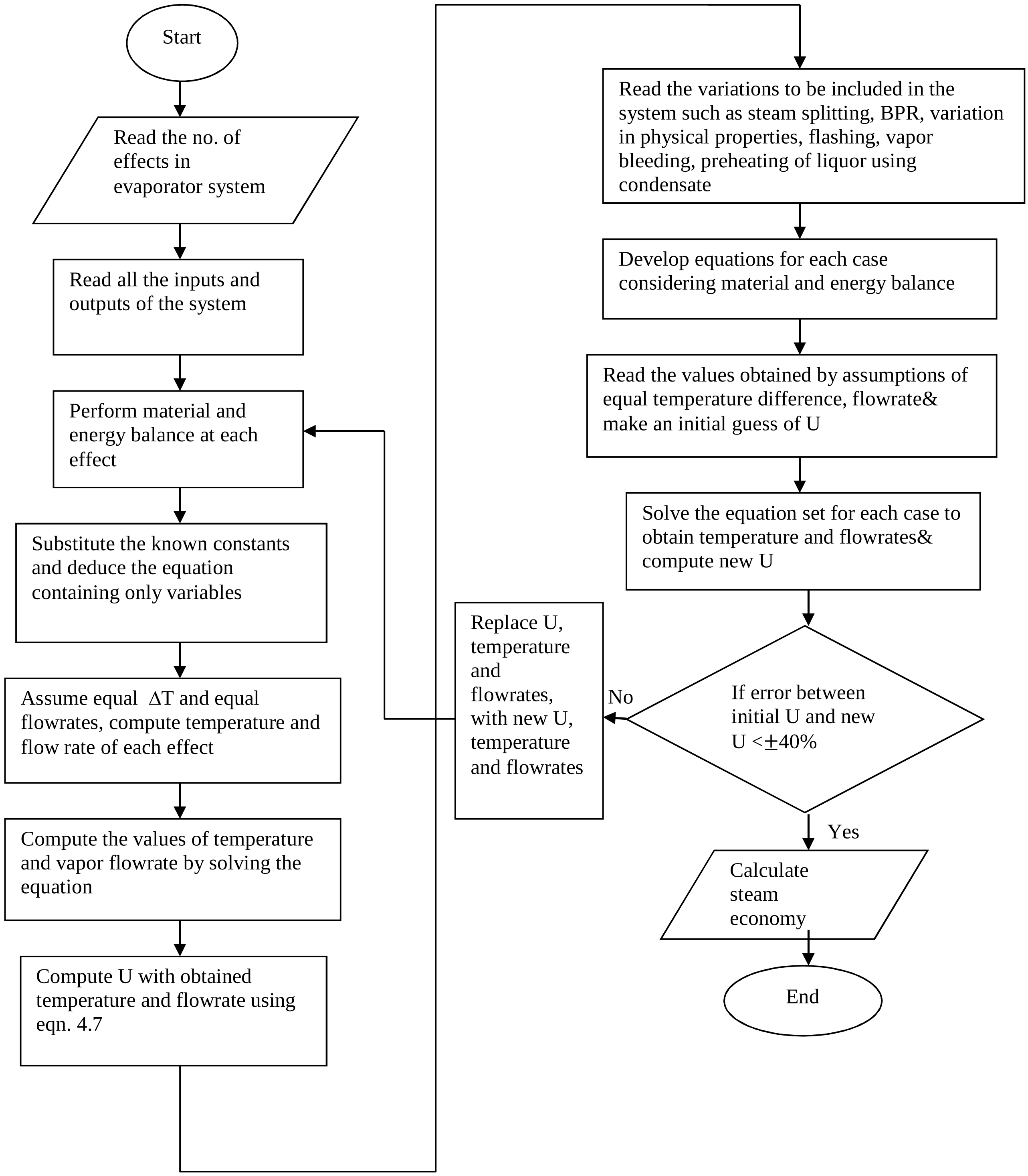

Figure 5.1: Algorithm for solution of final model

CHAPTER 6

RESULTS AND DISCUSSION

CHAPTER 6

RESULT AND DISCUSSION

The present Chapter shows the results obtained from the theoretical investigation carried out in the present work. The MEE system considered in this work is seven effect evaporator which is utilized for concentrating black liquor in typical Pulp and paper Industries as described in Chapter 3. For this system different models are developed for different configurations such as steam splitting, vapor bleeding and condensate flashing. These models consist of non-linear equations are developed in chapter 4. Temperature dependent physico-thermal properties and BPR are determined using the correlations developed in chapter 4. The set of non-linear equations developed is solved using Systems of Non-Linear Equations Software. The results obtained are discussed in the subsequent paragraphs:

6.1 SIMPLE SEVEN EFFECT SYSTEM WITH VARIABLE PHYSICAL PROPERTIES, BPR AND STEAM SPLITTING

The model for simple seven effect evaporator system with backward feed sequence is developed in Section 4.4.2. It takes into account variations in latent heat of vaporization, λ, and specific heat capacity, C_p, and BPR, τ, which are found using Eq. 4.1, 4.5 and 4.6, respectively. Along with this the present model also considers steam splitting. Total steam is splitted equally in the first and second effect and enters these effects at 140◦C and 147◦C as shown in Figure 3.1.

As this model accounts variation in physical properties and BPR an iterative method as described in chapter 5 is used. For this purpose initial values of temperatures and liquor flow rates are found based on assumption of equal ΔT as well as equal vaporization in each effect. Using these values λ, C_p, τ and U are computed. Values of U for each effect are obtained through Eq. 4.7. Then these predicted values are used in Eqs. 4.22 to 4.36 and solve it. Thus, results obtained are used to compute λ, C_p, τ and U and follow the second iteration. In this manner all iterations are solved till the values of U in two consecutive iterations are within ±40%. For clarity, results of all iterations of this model are reported in Table 6.1. It shows that final results are obtained in 9th

iteration where values of U fall within ±40% range. For this system steam consumption and economy are 2.296 kg/s and 4.334, respectively.

Table6.1: Results of simple seven effect evaporator system with variable λ, C_p and τ and steam splitting

Effect	1	2	3	4	5	6	7
Iteration 1							
U, kW/m^2°C	0.364	0.261	0.703	0.683	0.6803	0.6834	0.689
L, kg/s	3.07	4.862	6.653	8.445	10.236	12.03	13.82
X	0.6	0.3789	0.277	0.218	0.18	0.153	0.133
τ, °C	9.8	4.587	2.8406	2.0242	1.567	1.282	1.0886
T, °C	127.43	114.86	102.286	89.7	77.14	64.57	52
Iteration 2							
U, kW/m^2°C	0.159	0.208	0.491	0.601	0.659	0.737	0.864
L, kg/s	2.291	3.7897	5.073	7.585	9.84	11.834	13.58
X	0.804	0.486	0.363	0.243	0.187	0.155	0.135
τ, °C	16.346	6.869	4.289	2.351	1.649	1.307	1.11
T, °C	113.875	119.83	100.84	86.279	73.246	61.724	52
%Diff. of U	78.31	22.231	35.369	12.78	3.143	7.667	22.62
Iteration 3							
U, kW/m^2°C	0.2609	0.384	0.313	0.660	0.8079	0.992	1.295
L, kg/s	5.627	6.968	7.7066	9.577	11.237	12.704	14.012
X	0.327	0.264	0.239	0.192	0.164	0.145	0.131
τ, °C	3.652	2.655	2.298	1.709	1.393	1.200	1.071
T, °C	96.926	119.917	89.955	76.977	66.584	58.269	52
%Diff. of U	48.31	59.24	44.29	9.34	20.26	29.37	39.859
Iteration 4							
U, kW/m^2°C	0.164	0.276	0.2524	0.6206	0.791	1.0098	1.2675
L, kg/s	2.657	4.1588	5.257	7.614	9.7566	11.712	13.517
X	0.693	0.443	0.350	0.2419	0.1888	0.1572	0.136
τ, °C	12.58	5.89	4.057	2.338	1.668	1.32	1.116
T, °C	113.4854	128.98	90.8	76.74	66.041	57.844	52
%Diff. of U	45.19	32.81	21.52	6.15	2.097	1.785	2.16
Iteration 5							
U, kW/m^2°C	0.297	0.452	0.234	0.7099	0.965	1.292	1.751
L, kg/s	6.058	7.432	8.0135	9.744	11.302	12.716	14.015
X	0.304	0.247	0.229	0.189	0.1629	0.144	0.131
τ, °C	3.265	2.42	2.17	1.67	1.38	1.199	1.071
T, °C	101.281	125.665	83.4788	71.503	62.925	56.628	52
%Diff. of U	57.34	48.438	7.264	13.430	19.879	24.59	32.043
Iteration 6							

U, $kW/m^{2o}C$	0.183	0.303	0.213	0.673	0.925	1.246	1.748
L, kg/s	2.732	4.246	5.28	7.57	9.68	11.6414	13.48
X	0.674	0.433	0.348	0.243	0.19	0.158	0.136
τ, °C	11.989	5.699	4.029	2.357	1.68	1.33	1.120
T, °C	116.585	131.484	85.28	72.363	63.271	56.67	52
%Diff. of U	47.456	39.311	9.59	5.265	4.297	3.63	0.1519
Iteration 7							
U, $kW/m^{2o}C$	0.2918	0.4465	0.216	0.748	1.0686	1.479	2.164
L, kg/s	5.8214	7.215	7.793	9.5317	11.116	12.577	13.945
X	0.316	0.255	0.2367	0.1932	0.165	0.146	0.132
τ, °C	3.468	2.525	2.26	1.72	1.412	1.214	1.077
T, °C	103.63	126.75	80.37	69.0393	61.311	55.8	52
%Diff. of U	45.747	38.026	1.418	10.48	14.39	17.06	21.27
Iteration 8							
U, $kW/m^{2o}C$	0.184	0.306	0.203	0.709	1.0105	1.39	2.062
L, kg/s	2.835	4.345	5.344	7.593	9.676	11.625	13.472
X	0.649	0.4239	0.34	0.242	0.1904	0.158	0.136
τ, °C	11.243	5.49	3.955	2.3475	1.686	1.336	1.121
T, °C	116.2	131.32	82.47	70.2355	61.923	56.005	52
%Diff. of U	45.205	37.09530955	6.272	5.241	5.58	6.043	4.84
Iteration 9							
U, $kW/m^{2o}C$	0.284	0.436	0.2102	0.773	1.13	1.5854	2.406
L, kg/s	5.66	7.0605	7.6464	9.398	11.005	12.497	13.905
X	0.3255	0.2609	0.2409	0.196	0.1674	0.1474	0.1325
τ, °C	3.6203	2.605	2.3244	1.7524	1.4299	1.2242	1.0809
T, °C	104.008	126.79	78.88	67.929	60.622	55.4636	52
%Diff. of U	38.658	30.77	3.39	8.52	11.168	12.945	15.39

6.2 SEVEN EFFECT EVAPORATOR SYSTEM WITH CONDENSATE FLASHING

Condensate leaving from an effect is flashed to lower temperature to obtain vapour that can be used as heating medium is the subsequent effects along with the vapour emerging for previous effect. This can be used as energy reduction scheme to reduce energy demand from outside and enhance steam economy of the system. In the seven effect evaporator system there are 7 condensate flash tanks, PF1 to PF3, SF1 to SF4, placed between effects 3 and 7 as shown in Figure 3.1. The model of seven effect evaporator system with condensate flashing is developed under Section 4.4.3 and final results of the model are shown in the Table 6.2. It shows that product is concentrated upto 31.65%.

Table 6.2 Results of seven effect evaporator system with condensate flashing

Effect	1	2	3	4	5	6	7
U, $kW/m^{2o}C$	0.296	0.4303	0.2584	0.6955	0.839	0.9698	1.224
L, kg/s	5.82	7.006	7.54	9.064	10.65	12.184	13.692
X	0.3165	0.2629	0.2442	0.2032	0.1729	0.1512	0.1345
τ, °C	3.4697	2.6344	2.37	1.839	1.4899	1.2619	1.1002
Vapor from cond. flashing, kg/s	-	-	-	0.2585	0.1135	0.1199	0.1004
T, °C	106.313	126.792	89.459	77.188	67.201	58.669	52

Further, steam economy as well steam consumption of model for simple system, shown in Section 6.1, is compared with that of present model. The results of comparison are shown in Figure 6.1. It indicates that with the induction of condensate flashing steam consumption reduces by 21.78% and steam economy enhances up to 20.2%. The reason for such enhancement in steam economy is the decreased amount of evaporation rate. Table 6.2 shows that total evaporation is 9.79 kg/s however, it is 9.95 kg/s for simple system. Thus, system with condensate flashing reduces product concentration by 2.8% as shown in Figure 6.1. Though total evaporation is decreased with condensate flashing, it is obtained by consuming 1.845 kg/s of steam which is 21.78% less in comparison to simple model. This is due to availability of 0.5923 kg/s of additional vapor, generated through condensate flashing.

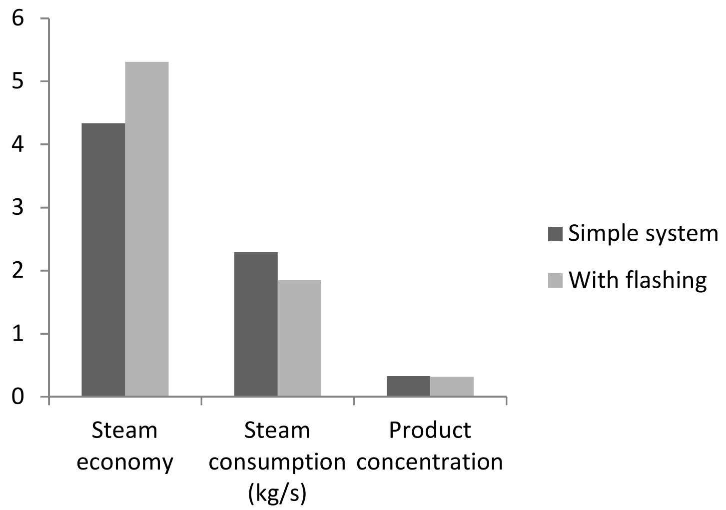

Figure 6.1 Comparison between simple backward sequence and backward sequence with flashing results

6.2.1 Optimization of number of flash tanks

In the present section an effort is made to optimize number of flash tanks. For this purpose, the system, shown in Figure 3.1, is solved with condensate flashing using different number of flash tanks. Maximum possible number of flash tanks that can be used in this system is eight. Amongst these seven flash tanks are placed as shown in Figure 3.1 and one additional flash tank, PF4, is placed between 6th and 7th effect. Considering eight flash tanks seven effect evaporator system is solved. The steam consumption for this system is found as 1.8387 kg/s and hence the steam economy is elevated to 5.3198 which is 0.25% more in comparison to the system shown in Figure 3.1. Thus, considering condensate flashing maximum possible steam economy of the system is 5.3198. Table 6.3 shows the results of seven effect system with condensate flashing using eight flash tanks.

Table 6.3: Results of seven effect system with condensate flashing using eight flash tanks

Effect	1	2	3	4	5	6	7
U, kW/m^2°C	0.2969	0.4307	0.259	0.6968	0.84	0.975	1.183
L, kg/s	5.83	7.013	7.548	9.067	10.646	12.175	13.67
X	0.316	0.2627	0.2441	0.2032	0.173	0.1513	0.1347
τ, °C	3.4611	2.6308	2.3674	1.8383	1.4909	1.2631	1.1018
Vapor from cond. flashing, kg/s	-	-	-	0.257	0.113	0.1194	0.124
T, °C	106.457	126.792	89.614	77.37	67.396	58.916	52

For optimizing number of flash tanks it is necessary to compute the contribution of each flash tank towards total evaporation so that tanks which are not contributing significantly can be eliminated from the system. For this purpose contribution of seven flash tanks, shown in Figure 3.1, towards total evaporation is calculated and presented in Table 6.4.

Table 6.4: Contribution of each flash tank in seven flash tank system

Flash tank	PF1	PF2	PF3	SF1	SF2	SF3	SF4
Vapour generated from flash tank (kg/s)	0.1725	0.0373	0.02937	0.086	0.0762	0.0905	0.1004
% contribution	1.67	0.36	0.285	0.83	0.74	0.88	0.974

It is observed from Table 6.4 that % contribution of PF3 is minimum amongst three primary flash tanks. However, PF3 cannot be eliminated as after this no flash tank is available to share the load of PF3. Hence, flash tank, PF2, is eliminated and its load is shifted to PF3. Now the seven effect evaporator system consists of six flash tanks instead of seven. Table 6.5 shows the results of this system. The obtained value of steam consumption is 1.8485 kg/s and steam economy is 5.278. Steam economy is lower by 0.55% than that for the system with seven flash tanks because less amount of additional vapor is generated through six flash tanks. Figure 6.2 shows the schematic diagram of seven effect evaporator system with six flash tanks.

Table 6.5: Results of system with condensate flashing using six flash tanks

Effect	1	2	3	4	5	6	7
U, kW/m^{2o}C	0.2976	0.4326	0.257	0.691	0.881	0.9584	1.21
L, kg/s	5.855	7.0456	7.58	9.103	10.701	12.186	13.686
X	0.3146	0.2615	0.2441	0.2024	0.1721	0.1512	0.1346
τ, °C	3.4382	2.613	2.353	1.8285	1.4812	1.262	1.1007
Vapor from cond. flashing, kg/s	-	-	-	0.2602	0.0768	0.1513	0.1012
T, °C	106.187	126.735	89.213	76.862	67.39	58.75	52

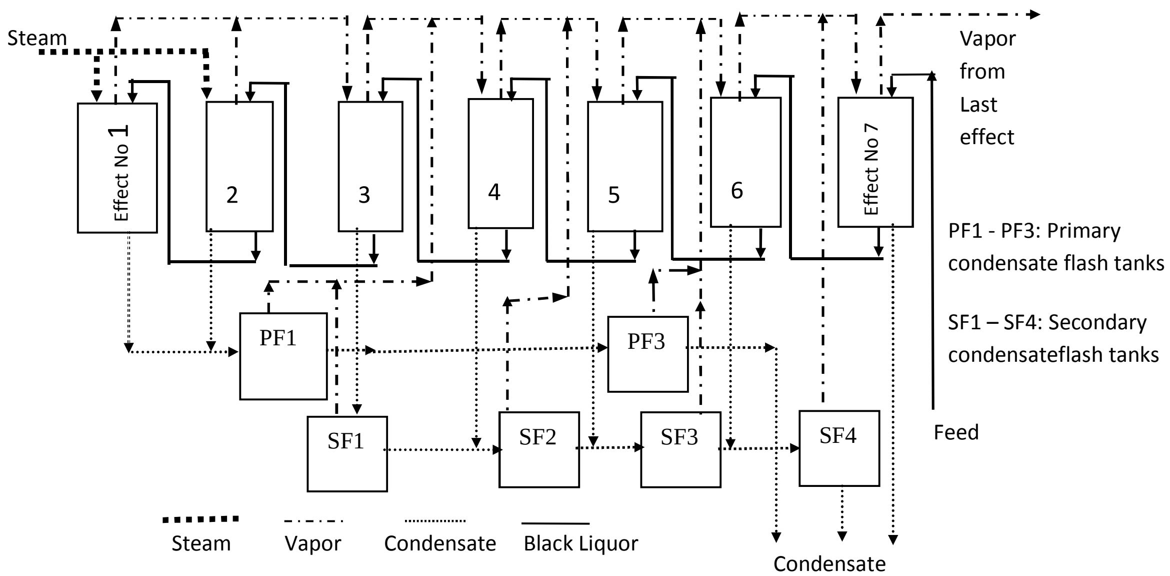

Figure 6.2: Schematic diagram of the seven effect system with flashing using 6 flash tanks

To refine the seven effect evaporator system further the contribution of six flash tanks, shown in Figure 6.2, is computed and shown in Table 6.6. It shows that amongst four secondary flash tanks SF2 is contributing least so it is removed by shifting its load to SF3. Now, the system is incorporating only five tanks, PF1, PF3, SF1, SF3 and SF4. The results of this system are shown in Table 6.7. The steam consumption and economy for this system are 1.8755 kg/s and 5.1917, respectively. The Figure 6.3 shows the schematic of seven effect evaporator system with five flash tanks.

Table 6.6: Contribution of each flash tank in six flash tanks system

Flash tank	PF1	PF3	SF1	SF2	SF3	SF4
Vapour generated from flash tank (kg/s)	0.1736	0.0657	0.0866	0.0768	0.0855	0.101
% contribution	1.69	0.64	0.843	0.748	0.833	0.985

Table 6.7: Results of system with condensate flashing using five flash tanks

Effect	1	2	3	4	5	6	7
U, $kW/m^{2o}C$	0.2986	0.4336	0.252	0.662	0.9545	1.0272	1.291
L, kg/s	5.874	7.0876	7.622	9.156	10.7887	12.25	13.728
X	0.3136	0.2599	0.2417	0.2012	0.1707	0.1504	0.1342
τ, °C	3.4214	2.59	2.335	1.8143	1.466	1.254	1.097
Vapor from cond. flashing, kg/s	-	-	-	0.2712	-	0.1456	0.09467
T, °C	106.01	126.514	87.969	75.031	66.33	58.305	52

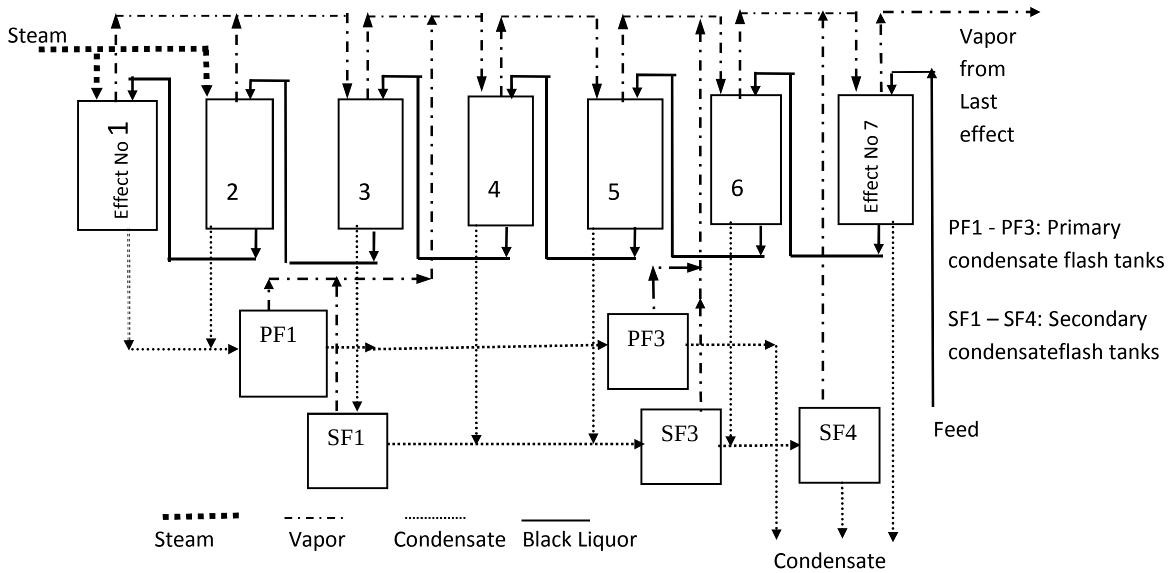

Figure 6.3: Schematic diagram of the seven effect system with flashing using five flash tanks

The comparison of results of seven effect evaporator system with eight, seven, six and five flash tanks is shown in Figure 6.4. It indicates that steam economy is maximum for system with eight flash tanks and minimum for system with five flash tanks. The reason of this variation is obviously the availability of vapor produced from flashing which is maximum for eight tanks system and minimum for five tanks system.

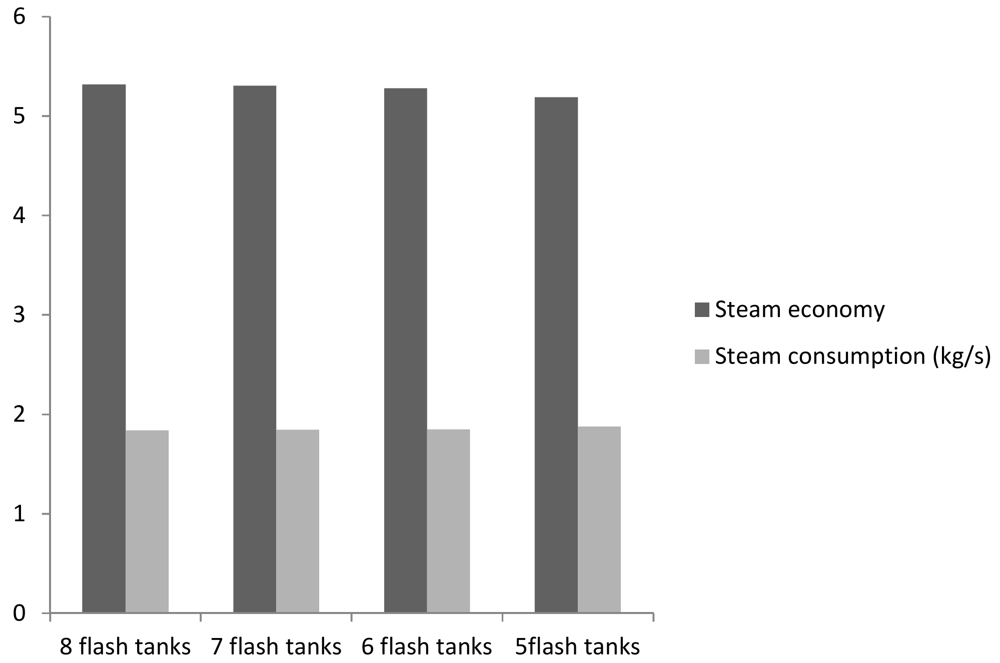

Figure 6.4: Comparison of systems with condensate flashing using different number of flash tanks

Further, to choose the best system economic analysis of four configurations, which are seven effect evaporator system with eight, seven, six and five flash tanks, are carried out. Here, operating cost, capital cost, total annual cost (TAC), profit and payback period for four configurations are presented. Operating cost is computed using steam consumption. The capital cost is predicted using number of flash tanks involved in the configuration. In fact, cost of seven evaporators is not accounted in capital cost as these are equal for all configurations and thus, it will not affect the results of comparative study. For each configuration profit is computed by deducting steam consumption without flashing and with flashing. The economic analyses of four configurations are compared in Table 6.8. It shows that TAC is maximum for system with five flash tanks but it is only 1.9% more in comparison to the system with eight flash tanks which is not significant. In the similar lines profit and payback period are also not differ appreciably for four configurations. Thus, system with five flash tanks can be selected as optimum as it gives less complex network in comparison to other configurations.

Table 6.8: Economic analysis of four configurations

Parameter	8 flash tanks	7 flash tanks	6 flash tanks	5 flash tanks
Operating cost (Lac/year)	1323.9	1328.4	1330.9	1350.4
Capital cost (Lac)	18.01	16.18	15.06	12.14
Profit (Lac/year)	329.3	324.7	322.2	302.76
Payback (days)	20	18	17	15
TAC (Lac/year)	1325.7	1330.02	1332.4	1351.6

6.3 SEVEN EFFECT EVAPORATOR SYSTEM WITH VAPOUR BLEEDING

Vapor bleeding is done to preheat the liquor near to the temperature of the effect before it is entering into the effect so that the liquor can quickly attain the boiling temperature inside the effect. A portion of stream of vapor extracted from the stream entering as a heating medium to one of the effects is used to preheat the liquor that is coming out from one effect. In the present work two configurations are considered. In both cases four pre heaters are placed between effects 3 and 7 as shown in Figure 4.10. In case of first configuration (configuration 1), the vapor required for pre heaters placed between 2^{nd} and 3^{rd}, 3^{rd} and 4^{th}, 4^{th} and 5^{th}, 5^{th} and 6^{th} effects are bled from V_2, V_3, V_4,and V_5, respectively. The model of this system is developed under Section 4.4.4 and final results of the model are shown in the Table 6.9. It shows that bled vapor flow rates from streams V'_2, V'_3, V'_4 and V'_5 are 0.07835, 0.06266, 0.03956 and 0.00571 kg/s, respectively. The total rate of evaporation is 9.862 kg/s. The steam consumption is found to be 2.035 kg/s and hence the steam economy is 4.846.

Table 6.9: Results of seven effect evaporator system with vapor bleeding (configuration 1)

Effect	1	2	3	4	5	6	7
U, kW/m^{2}°C	0.2633	0.3793	0.323	0.6872	0.835	1.007	1.277
L, kg/s	5.749	7.072	7.786	9.631	11.274	12.73	14.025
X	0.3204	0.2605	0.2366	0.1913	0.1634	0.1447	0.1313
τ, °C	3.5351	2.5989	2.2659	1.6968	1.3875	1.1976	1.0704
Amount of vapor bled, kg/s	-	0.07835	0.06266	0.03956	0.00571	-	-
T, °C	95.446	117.928	88.987	76.57	66.543	58.36	52

Further, steam economy as well steam consumption of model for simple system, shown in Section 6.1, is compared with that of present model. It is observed that with the addition of vapour bleeding steam consumption reduces and steam economy enhances. Table 6.9 shows that total evaporation is 9.862 kg/s however; it is 9.95 kg/s for simple system. Though total evaporation is decreased with vapour bleeding, it is obtained by consuming 2.035 kg/s of steam which is 12.05% less in comparison to simple model.

For the second configuration (configuration 2), vapor required for pre heaters placed between 3rd and 4th, 4th and 5th, 5th and 6th and 6th and 7th effects are bled from V_3, V_4, $V_5$and V_6, respectively. Results of this model are shown in the Table 6.10.

Table 6.10 shows that bled vapor flow rates from streams V'_3, V'_4, V'_5 and V'_6 are 0.0598, 0.0624, 0.0573, 0.0449 kg/s, respectively. The steam consumption is found to be 2.0133kg/s with the corresponding steam economy of 4.905 however; it is 2.296 kg/s and 4.433 for simple system. Enhancement in economy is due to the appropriate utilization of driving force (ΔT) for sensible heating by low pressure vapor (with high latent heat) which improves the value of steam economy.

Table 6.10: Results of seven effect evaporator system with vapor bleeding (configuration 2)

Effect	1	2	3	4	5	6	7
U, $kW/m^{2o}C$	0.2635	0.3793	0.3189	0.673	0.826	1.017	1.33
L, kg/s	5.735	7.039	7.739	9.606	11.273	12.748	14.056
X	0.3212	0.2617	0.238	0.1918	0.1634	0.1445	0.1311
τ, °C	3.5351	2.5989	2.2659	1.6968	1.3875	1.1976	1.0704
Amount of vapor bled, kg/s	-	-	0.0598	0.0624	0.0573	0.0449	-
T, °C	96	118.4	89.037	76.33	66.19	58.097	52

Figure 6.5 represents the comparison between two configurations. It is observed that configuration 2 is better than the one as it has 1.21% more steam economy and 1.1% less steam consumption. However, product concentration in both configurations is equal.

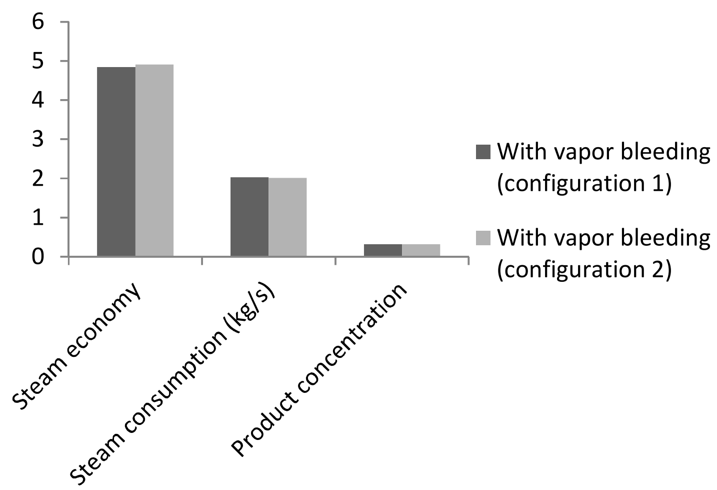

Figure 6.5: Comparison between configuration 1 and 2 for system with vapor bleeding

6.4 SEVEN EFFECT EVAPORATOR SYSTEM WITH VAPOUR BLEEDING AND CONDENSATE FLASHING

In the present section seven effect system is considered which includes steam splitting, variation in physical properties, condensate flashing and vapor bleeding together. The part of vapor that enters to the next effect is bled to preheat the liquor entering the following effect and after that vapor is also used for flashing. It is observed from section 6.2.1 that the seven effect evaporator system with condensate flashing using five flash tanks is optimum. Hence five flash tanks system with vapor bleeding is considered in the present section to study the enhancement in steam economy. For this particular case vapor bleeding is done according to configuration 2 discussed in section 6.3 is considered. Table 6.11 shows the results obtained for the present model developed in Section 4.4.5 which includes the variation of vapor bleeding as well as condensate flashing. It is observed that the steam consumption reduces to 1.8542 kg/s and steam economy enhances to 5.549.

Table 6.11: Results of system with vapor bleeding and condensate flashing

Effect	1	2	3	4	5	6	7
U, $kW/m^{2o}C$	0.263	0.3426	0.39	0.644	0.786	0.819	0.9499
L, kg/s	5.321	6.458	7.174	8.9	10.64	12.177	13.707
X	0.3462	0.2852	0.2568	0.207	0.1731	0.1513	0.1344
τ, °C	3.9818	2.9683	2.5458	1.884	1.492	1.2628	1.0988
Vapor from cond. flashing, kg/s	-	-	-	0.213	-	0.1797	0.1299
Amount of vapor bled, kg/s	-	-	0.054	0.0606	0.0743	0.0729	-
T, °C	105.37	118.307	95.08	81.73	71.02	60.76	52

Further, steam economy as well steam consumption of model shown in Section 6.2 is compared with that of present model and simple system. The results of comparison are shown in Figure6.6. It is concluded from this figure that with the addition of condensate flashing and vapour bleeding in the system steam consumption reduces and steam economy enhances. The reason for such enhancement in steam economy is the decreased amount of evaporation rate. However, it is achieved by consuming 1.8542 kg/s of steam which increases steam economy upto 5.549. It is obtained that the consumption of steam in present model is 21.29% less in comparison to simple model and 1.15% less in comparison to evaporator system with flashing. The reason for such increment in steam economy is discussed under Sections 6.2 and 6.4. The schematic diagram of this system is shown in Figure 6.7.

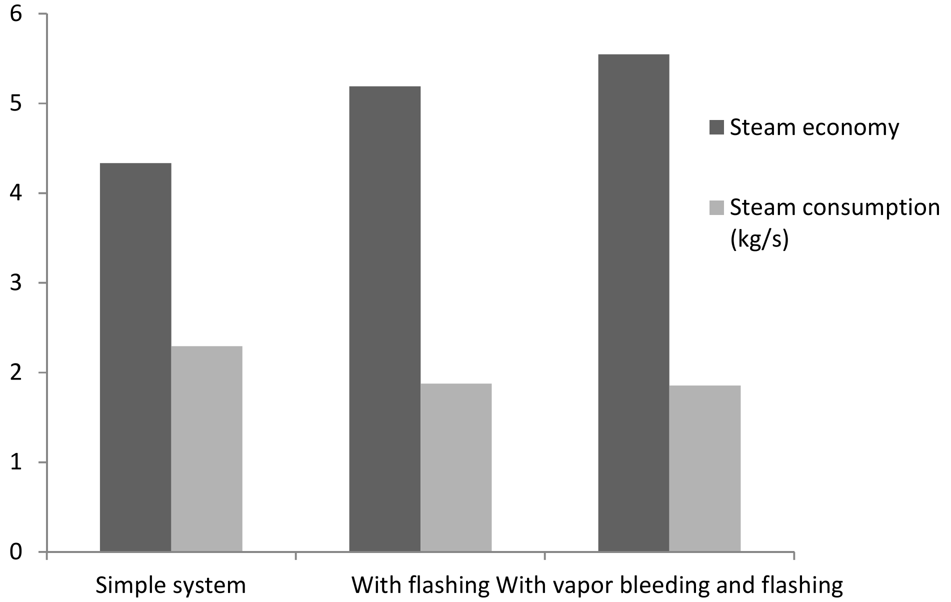

Figure 6.6: Comparison of simple system, system with flashing and system with vapor bleeding and flashing

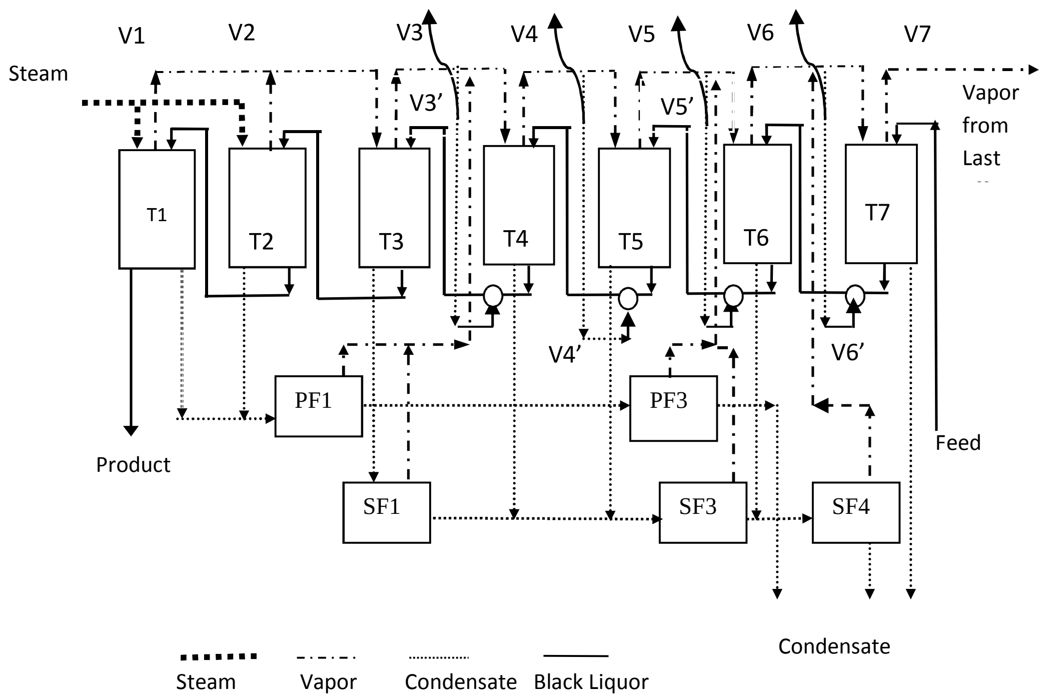

Figure 6.7: Schematic diagram of seven effect system with vapor bleeding and condensate flashing

6.5 SEVEN EFFECT EVAPORATOR SYSTEM WITH PREHEATING OF LIQUOR USING SENSIBLE HEAT OF CONDENSATE

In this section the liquor is preheated near to the temperature of effect before it is entering into the effect. Under Section 6.3 preheating of liquor is done through bled vapor, however, in this case condensate of steam/vapor is used to preheat the liquor, which is entering into that effect using a counter current heat exchanger. Condensates of live steams and condensates of vapor chests of 3rd, 4th and 5th effect are utilized in the process to preheat the liquor coming from the 4th, 5th, 6th and 7th effect, respectively. The final results of the model of seven effect evaporator system with preheating of liquor using condensate are shown in Table 6.12. It shows that total evaporation is 9.22 kg/s; however, it is 9.95 kg/s for simple system. The steam consumption is found to be 1.676 kg/s and hence the steam economy is 5.503.

Table 6.12: Results of seven effect evaporator systemwith preheating of liquor using condensate

Effect	1	2	3	4	5	6	7
U, kW/m^{2o}C	0.3075	0.435	0.2679	0.7103	0.885	1.1196	1.465
L, kg/s	6.39	7.622	8.1066	9.78	11.33	12.745	14.03
X	0.288	0.241	0.227	0.188	0.162	0.144	0.131
τ, °C	3.015	2.334	2.141	1.662	1.379	1.195	1.0699
T, °C	99.76	122.27	86.205	74.236	64.83	57.522	52

Further, steam economy as well as steam consumption of model for simple system and vapor bleeding system, shown in Section 6.1 and section 6.3 respectively, is compared with that of present model. It is observed that with the addition of preheating of liquor using condensate steam consumption reduces upto 31.22% and steam economy enhances upto 23.77% compared to simple system. Consumption of steam in the present model is 18.285% less and steam economy is 11.49% more in comparison to vapor bleeding model. The reason of reduction in steam consumption is that after preheating liquor is entering at temperature of effect and thus steam/vapor is used only for evaporation instead of sensible heating.

6.6 SEVEN EFFECT EVAPORATOR SYSTEM WITH PREHEATING OF LIQUOR USING SENSIBLE HEAT OF CONDENSATEAND CONDENSATE FLASHING

Here seven effects system, which includes preheating of liquor through condensate and flashing together, is considered. It is done as the condensate leaving the exchanger after preheating is at significantly higher temperature and its heat can further be utilized through flashing in the effects, which are being operated at low temperature. For this purpose seven effect system with preheating of liquor through condensate is modified to incorporate five flash tanks, PF1 to PF3, SF1 and SF2, as shown in Figure 6.8. In these tanks condensates of live steam C_{01}, C_{02} and condensate from third effect vapour chest C_1 are being flashed. Hence five flash tanks system with preheating of liquor through condensate is considered in the present section to study the enhancement in steam economy. The model for this system is developed in Section 4.4. Table 6.13 shows the results obtained for this model. It is observed that the modified seven effect evaporator system consumes 1.583 kg/s of steam and steam economy enhances to 5.807.

Table 6.13: Results of seven effect evaporator system with preheating of liquor using condensate and condensate flashing

Effect	1	2	3	4	5	6	7
U, kW/m^{2o}C	0.307	0.439	0.271	0.740	0.893	1.036	1.213
L, kg/s	6.418	7.615	8.07	9.688	11.19	12.6	13.93
X	0.287	0.242	0.228	0.190	0.164	0.146	0.132
τ, °C	2.99	2.338	2.155	1.683	1.400	1.212	1.0787
Vapor from cond. flashing, kg/s	-	-	-	-	0.02833	0.0527	0.0383
T, °C	99.53	122.936	87.425	75.985	66.66	58.72	52

Further, steam economy, steam consumption and product concentration of present model is compared with that of simple system and model with vapor bleeding and flashing. The results of comparison are shown in Figure 6.9. From this figure it is concluded that with the induction of preheating of liquor using condensate and flashing in the system steam consumption reduces and steam economy enhances. The reason for such enhancement in steam economy is the decreased amount of evaporation rate. Total evaporation is 9.193 kg/s in comparison to simple system which has 9.95 kg/s of evaporation. It is observed that the consumption of steam in present model is 36.76% less in comparison to simple model and 15.78% less in comparison to evaporator system with condensate flashing and vapor bleeding. Steam economy of this model is increased upto 23.77 % compared to simple system.

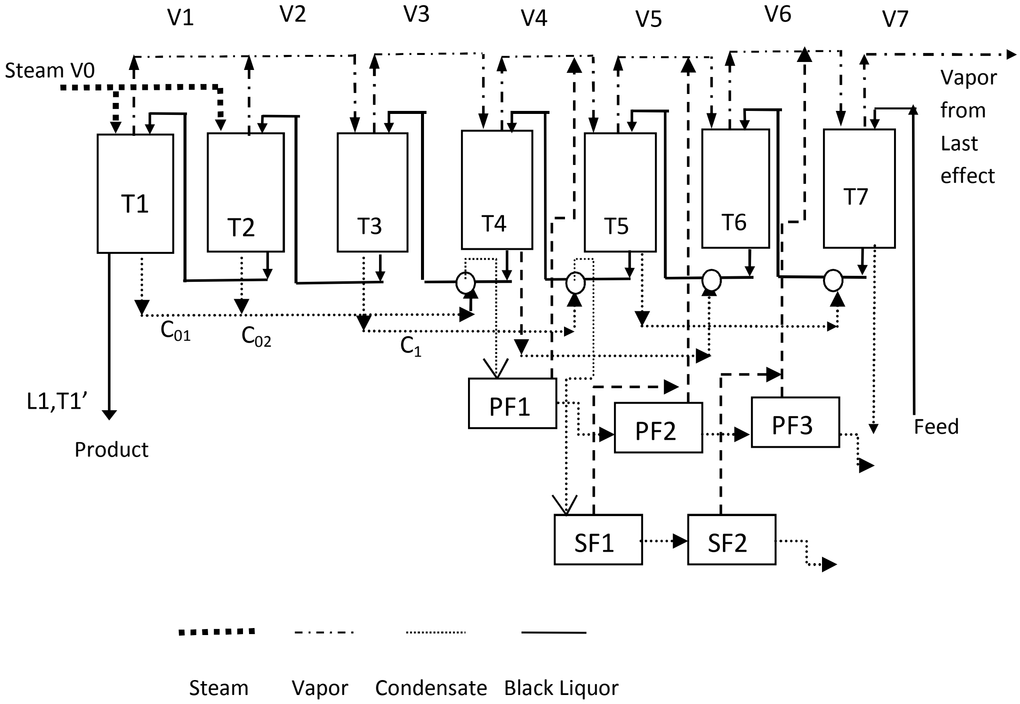

Figure 6.8: Schematic diagram of seven effect system preheating of liquor using condensate and with flashing

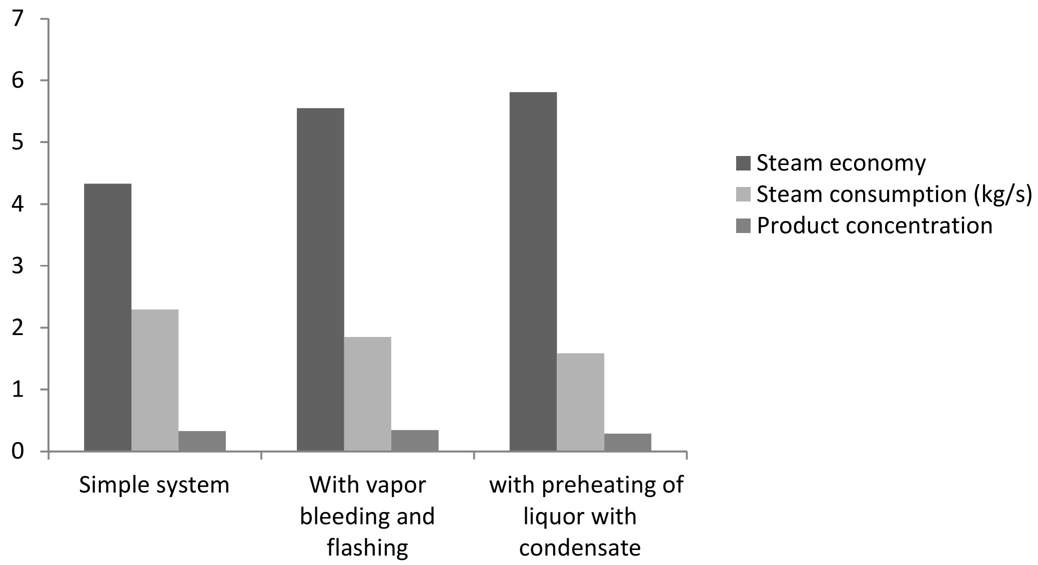

Figure 6.9: Comparison of simple system, system with vapor bleeding and flashing and system with flashing and preheating of liquor using condensate

6.7 PINCH ANALYSIS OF MEE SYSTEM

The heat integration options discussed under Section 6.2 to 6.6 are considered for enhancing steam economy of MEE system. These options are condensate flashing, vapor bleeding, preheating of liquor using sensible heat of condensate, etc.

Another heat integration technology is pinch analysis (Linnhoff et al., 1982) which may be applied to MEE system. For this purpose the simple seven effect evaporator system, shown in Figure 4.5, is considered. Based on equal driving force as well as equal vaporization in each effect, temperatures and concentration of each effect is predicted. Using these parameters physical properties and BPR are computed. These parameters are considered in the equations of the system. Further, to apply pinch analysis it is considered that total sensible heat required in the system is provided outside the effect and thus, liquor is entering the effect at boiling temperature. Consequently, only evaporation is taking place inside the effect. To consider this effect the equations of system shown through Eq. 4.17 to 4.30 are modified as liquor entering and leaving the effect at same temperature i.e. effect temperature plus BPR. The modified equations are solved to get new values of temperatures, concentration as well as steam consumption. The results are shown in Table 6.14. For this system total steam consumption is found as 0.416 kg/s.

Table 6.14 Results for first iteration

effect	Temp. (C)	Flowrate (kg/sec)	X	BPR	Cp (KJ/kg K)	λ (KJ/kg)	U(kW/m2 K)
1	84.84	6.412	0.2873	2.9999	3.537	2296.026	0.266
2	127.72	7.347	0.2507	2.4602	3.620	2179.569	0.461
3	91.377	7.796	0.2363	2.2618	3.652	2278.93	0.2649
4	80.28	9.286	0.1984	1.7806	3.738	2307.798	0.763
5	70.09	10.799	0.1706	1.4643	3.801	2333.713	0.823
6	60.499	12.312	0.1496	1.2462	3.848	2357.5519	0.8708
7	52	13.818	0.1333	1.0887	3.886	2378.2524	0.976

To consider the heat associated with sensible heating the stream data of different streams are extracted from the system and reported in Table 6.15. The pinch analysis is applied to the stream data considering ΔT_{min} as 10°C and composite curve is shown in Figure 6.10. The minimum hot and cold utility of the system is 351.69kW and 21775.18 kW, respectively. The hot composite curve shows total heat available with different vapor streams. Similarly, cold composite curve represents the total heat required by all liquor streams which need to be preheated.

Table 6.15 Stream data of seven effect evaporator system

Stream no.	Stream name	T_s (°C)	T_t(°C)	Cp (kJ/kg°C)	m (kg/s)	CP (kW/°C)
1	Cold	53.088	61.745	3.886	13.818	53.691
2	Cold	61.745	71.551	3.849	12.312	47.38
3	Cold	71.551	82.063	3.8013	10.799	41.05
4	Cold	82.063	93.639	3.738	9.286	34.71
5	Cold	93.64	130.18	3.653	7.796	28.47
6	Hot	84.84	83.84	2652.099	0.935	2479.71
7	Hot	127.72	126.72	2717.025	0.449	1219.94
8	Hot	91.38	90.38	2662.662	1.49	3967.367
9	Hot	80.28	79.28	2644.593	1.513	4001.269
10	Hot	70.08	69.08	2627.38	1.513	3975.225
11	Hot	60.5	59.5	2610.662	1.506	3931.65
12	Hot	52	51	2595.412	1.793	4653.86

In Figure 6.10 the shaded area shows the amount of heat associated with vapor streams which is provided to liquor streams under the curve. The part of cold composite curve above the shaded area is the heat provided through hot utility. Thus, if the heat available in shaded area as well as hot utility is fulfilled from outside then no sensible heating is required inside the effect. Consequently, liquor streams enter and leave the effect at boiling temperature and inside the effect only evaporation takes place. Considering this fact the steam consumption is computed as 0.416 kg/s. Figure 6.10 shows that total amount of heat required for sensible heating of liquor as 2989 kW. Assuming this heat is provided by steam, the amount of steam required is 1.337 kg/s. Thus, total steam consumption in the system is found as 1.753 kg/s, which gives steam economy as 5.246.

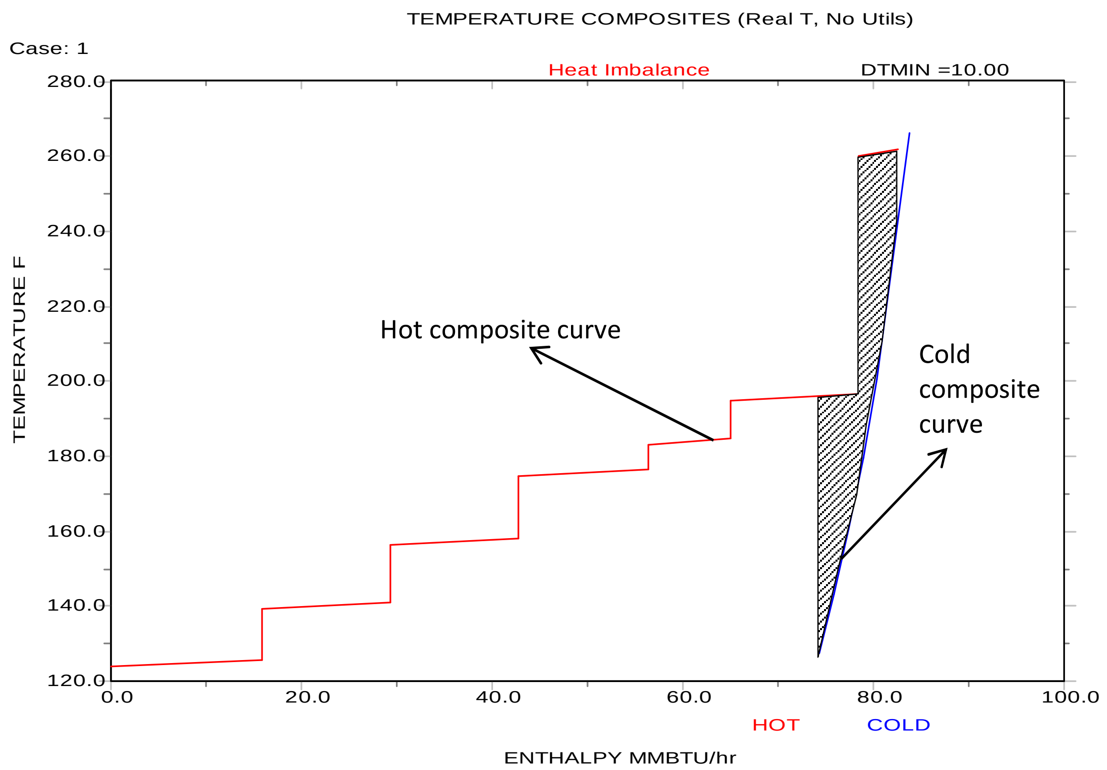

Figure6.10 Composite curve for seven effect evaporator system

Results shown in Table 6.14 and Figure 6.10 are for first iteration. The sequence of computation discussed above is followed for other iterations also till the value of U fall within ±40%. The results of all iterations are summarized in Table 6.16. It shows that steam economy of the seven effect evaporator system applying pinch analysis is found as 4.292, which is almost equal to steam economy of the system discussed in Section 6.1.

Table 6.16 Results of Aspen Pinch analysis

Iteration no.	Steam required for evaporation (kg/s)	Heat available in shaded area (kW)	Hot utility (kW)	Steam for sensible heating(kg/s)	Steam consumption (kg/s)	Steam economy
1	0.416	2402.6	351.69	1.337	1.753	5.246
2	1.286	2227.3	307.7	1.147	2.433	4.292

CHAPTER 7

CONCLUSION

CHAPTER 7

CONCLUSIONS

A phenomenological and heuristic mathematical model for a multiple effect evaporator is developed in present work. The mathematical model considers the variation of thermo physical properties within the process. The salient conclusions of the present work are as follow:

- The model considered which is based on set of nonlinear equations, directs almost all difficulties of real MEE system such as variation in physical properties, BPR, steam splitting, feed, product and condensate flashing and vapor bleeding.
- The economy of simple system is 4.334 which increase by 20.2%, 12.4%, 23.7%, 24.6 % and 29.05% by inducting condensate flashing, vapor bleeding, preheating of liquor with condensate, vapor bleeding and flashing and preheating of liquor with condensate and flashing respectively.
- Based on economic analysis as well as steam economy it is concluded that the seven effect evaporator system can run effectively with five flash tanks instead of seven in actual flowsheet. Thus, this approach gives a less complex network for evaporator system.
- The two different types of configuration of vapor bleeding are considered and comparison of both configurations is done. It is observed that steam economy for configuration two is more compared to configuration one.

- Considering the optimum number of flash tanks and the best configuration of vapor bleeding, a system was designed. This system enhances the steam economy by 24.6% and reduces the steam consumption by 21.3% in comparison to simple system.
- Liquor heating using sensible heat of condensate contributes considerably to reduce steam consumption. Besides, it produces less complex MEE network in comparison to other model.
- Considering the maximum possible number of flash tanks and pre heating of liquor with condensate, a final system was designed. The steam economy was 23.77% more and steam consumption 36.76 % less in comparison to simple system.
- Pinch analysis of the MEE network has also been done using ASPEN Pinch software. It is found that the result obtained is very close to simulated values.

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APPENDIX

APPENDIX

SAMPLE CALCULATION

Sample Calculations for Design of seven effect evaporator system with vapor bleeding and condensate flashing (Figure 6.8)

1.1 The following data were assumed for the design of evaporators:

Feed flow rate, m_f= 15.611 kg/s

Feed solid mass fraction, x_f = 0.118

Last effect solid mass fraction, x_p= 0.6

Feed temperature, T_f = 64.7 ˚C

Live steam temperature in effect 1 =140 ˚C

Live steam temperature in effect 2 = 147 ˚C

Vapor temperature of last effect = 52 ˚C

Area of first and second effect = 540 m^2

Area of third to sixth effect = 660 m^2

Area of seventh effect = 690 m^2

1.2 Equal temperature drop and equal vaporization in each effect were assumed initially to calculate temperatures and liquor flow rates for each effect.

$$\Delta T = \frac{(T_S - T_7)}{n} \quad (1)$$

ΔT= (140 – 52)/7 = 12.57 ˚C

$T_1 = T_S - \Delta T$ = 140 – 12.57 = 127.43 ˚C

$T_2 = T_1 - \Delta T$ = 127.43 – 12.57 = 114.86 ˚C

$T_3 = T_2 - \Delta T$ = 114.86 – 12.57 = 102.28 ˚C

$T_4 = T_3 - \Delta T = 102.28 - 12.57 = 89.714$ ˚C

$T_5 = T_4 - \Delta T = 89.714 - 12.57 = 77.143$ ˚C

$T_6 = T_5 - \Delta T = 77.143 - 12.57 = 64.57$ ˚C

The overall component balance

$$F x_f = L_1 x_1$$

$L_1 = (15.611 \times 0.118)/0.6 = 3.07$ kg/s

Equal vaporization was assumed

$$V_1 = V_2 = \ldots\ldots = V_7 = (F - L_1)/n = (15.611 - 3.07)/7 = 1.792 \text{ kg/s} \quad (2)$$

$L_7 = 15.611 - 1.792 = 13.82$ kg/s

$L_6 = 13.82 - 1.792 = 12.03$ kg/s

$L_5 = 12.03 - 1.792 = 10.236$ kg/s

$L_4 = 10.236 - 1.792 = 8.44$ kg/s

$L_3 = 8.44 - 1.792 = 6.653$ kg/s

$L_2 = 6.653 - 1.792 = 4.862$ kg/s

1.3 calculation of intermediate composition of liquor, boiling point elevation, specific heat, heat of vaporization and overall heat transfer coefficient

$x_7 = (15.611 \times 0.118)/13.82 = 0.133$

$x_6 = (13.82 \times 0.133)/12.03 = 0.153$

$\tau_7 = 20(0.1+0.133)^2 = 1.0886$ ˚C

$Cp_7 = 4.187(1-(0.54 \times 0.133)) = 3.885$ kJ/ kg K

$\lambda_7 = (-0.0028 \times 52 \times 52) - (2.1207 \times 52) + 2496.1 = 2378.25$ kJ/kg

$$\frac{U_7}{2} = 0.1396 \left(\frac{\Delta T}{40}\right)^{-0.7949} \left(\frac{x_{avg}}{0.6}\right)^{0.0} \left(\frac{F_{avg}}{25}\right)^{0.1673} \quad (3)$$

$\Delta T = 64.57 - 52 - 1.0886 = 11.48$

$x_{avg} = (0.118+0.133)/2 = 0.1255$

F_{avg} = (15.611+13.82)/2 = 14.716

$$\frac{U_7}{2} = 0.1396\left(\frac{11.48}{40}\right)^{-0.7949}\left(\frac{0.1255}{0.6}\right)^{0.0}\left(\frac{14.716}{25}\right)^{0.1673}$$

U_7 = 0.689 kW/m^2 K

Similarly the values of intermediate composition of liquor, boiling point elevation, specific heat, heat of vaporization and overall heat transfer coefficient for other effects were also calculated which are shown in table 1

Calculation of enthalpy of liquor and vapor

h_0 = (4.2113×(140+147)/2) - 1.9114 = 588.43 kJ/kg

h_{0L} = (4.2221×102.28) - 2.6593 = 428.84 kJ/kg

H_{0V} = (-0.0028×102.28×102.28) + (2.1093×102.28) + 2493.3 = 2679.76 kJ/kg

Similarly the values of enthalpy of liquor and vapor at different intermediate temperatures were calculated which are shown in table 1.

Table 1: Sample calculation for other effects

Effect	temp (˚C)	flowrate (kg/s)	X	BPR	Cp (KJ/kg K)	λ (KJ/kg)	U(KW/m 2 K)	h (KJ/kg)	H (KJ/kg)
1	127.429	3.0701	0.6	9.8	2.830	2180.39	0.364	535.35	2716.61
2	114.857	4.8617	0.379	4.587	3.330	2215.58	0.2609	481.78	2698.63
3	102.286	6.653	0.277	2.841	3.561	2249.88	0.7029	428.84	2679.75
4	89.714	8.4448	0.218	2.024	3.693	2283.30	0.6832	375.90	2659.99
5	77.143	10.236	0.18	1.567	3.780	2315.84	0.6802	322.96	2639.35
6	64.571	12.028	0.153	1.282	3.840	2347.49	0.683	270.02	2617.826
7	52	13.819	0.133	1.088	3.885	2378.25	0.6890	217.08	2595.41

1.4 Flash tank calculation

For first primary flash tank

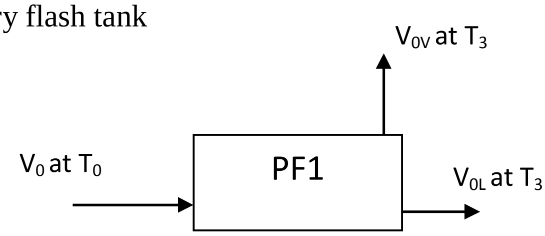

Figure1: Schematic diagram PF1

$$V_{0v} = V_0 \left[\frac{(h_0 - h_{0L})}{(H_{0v} - h_{0L})}\right] \tag{4}$$

Here V_0 is amount of vapour entering the first primary flash tank PF1 at T_0 [(140+147)/2=143.5˚C] which is flashed at T_3 (102.86˚C).

Vapor flow rate from PF1

$$V_{0V} = V_0\ (588.43 - 428.84)/(2679.76 - 428.84) = 0.0709\ V_0 \tag{5}$$

Condensate flow rate from PF1

$$V_{0L} = (1 - 0.0709)\ V_0 = 0.9291\ V_0 \tag{6}$$

Similarly the flow rates for other flash tanks,

Vapor flow rate from PF2

$$V_{0LV1} = V_0\ (428.84 - 322.96)/(2639.35 - 322.96) = 0.04247\ V_0 \tag{7}$$

Condensate flow rate from PF2

$$V_{0LL1} = (0.9291 - 0.04247)\ V_0 = 0.8866\ V_0 \tag{8}$$

Vapor flow rate from SF1

$V_{1V} = (V_1 + V_2)$ (508.25 - 428.84)/(2679.76 – 428.84) = 0.0353 $(V_1 + V_2)$ (9)

Condensate f1low rate from SF1

$V_{1L} = (1 – 0.0353) (V_1 + V_2) = 0.9647 (V_1 + V_2)$ (10)

Vapor flow rate from SF2

$V_{2V} = (V_{1L} + V_{1V} + V_{0V} + V_3 + V_4)$ (375.9 – 322.96)/(2639.35 – 322.96) (11)

$= 0.02286 (V_{1L} + V_{1V} + V_{0V} + V_3 + V_4)$

Condensate flow rate from SF2

$V_{2L} = (1 – 0.02286) (V_{1L} + V_{1V} + V_{0V} + V_3 + V_4)$ (12)

$= 0.977 (V_{1L} + V_{1V} + V_{0V} + V_3 + V_4)$

Vapor flow rate from SF3

$V_{3V} = (V_{2L} + V_{2V} + V_{0LV1} + V_5)$ (322.96 – 270.018)/(2617.826 – 270.018) (13)

$= 0.02255 (V_{2L} + V_{2V} + V_{0LV1} + V_5)$

Condensate flow rate from SF3

$V_{3L} = (1 – 0.02255) (V_{2L} + V_{2V} + V_{0LV1} + V_5)$ (14)

$= 0.9775 (V_{2L} + V_{2V} + V_{0LV1} + V_5)$

1.5 Vapor Bleeding calculations

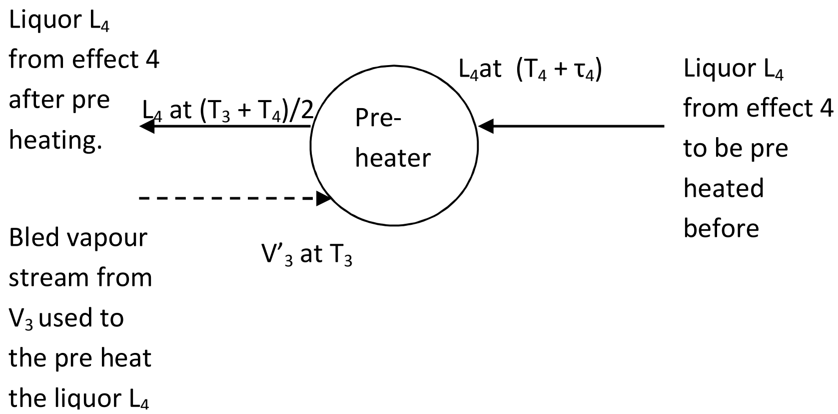

Figure2: Schematic diagram of pre-heater 1

Material balance around pre- heater 1 is given as:

$$V_3'\lambda_3 = L_4 C_{p4}\left(\frac{(T_3+T_4)}{2} - T_4 - \tau_4\right) \tag{15}$$

V_3' = 8.4448×3.693× {(89.714+102.286)/2 – 89.714 - 2.024}/2249.88 = 0.0591 kg/s

V_4' = 0.0788 kg/s

V_5' = 0.09846 kg/s

V_6' = 0.117 kg/s

The expressions and calculated values mentioned in the above sections are used in the set of non-linear equations developed in section 4.4.5 of chapter 4. Now this set of non-linear equations are solved iteratively in systems of non-linear equations software. Thus, results obtained are used to compute λ, C_p, τ, U, bled vapor flow rate and vapor flow rates from flash tanks and follow the second iteration. In this manner all iterations are solved till the values of U in two consecutive iterations are less than 40%. The values of final iteration are shown in table 2.

Table 2: Values of final iteration

Effect No.	temp (C)	flowrate (kg/sec)	x	BPR	Cp (kJ/kg K)	λ (kJ/kg)	U(kW/m2 K)	Vapor from flash tank	Bled vapor flow rate
1	105.37	5.321	0.3462	3.9818	3.404	2241.55	0.263	-	-
2	118.307	6.458	0.2852	2.9683	3.542	2206.016	0.342	-	-
3	95.08	7.174	0.2568	2.5458	3.606	2269.15	0.390	-	0.054
4	81.73	8.9	0.207	1.8847	3.719	2304.072	0.644	0.213	0.0606
5	71.02	10.64	0.1731	1.492	3.795	2331.365	0.7863	-	0.0743
6	60.76	12.177	0.1513	1.2628	3.845	2356.909	0.8187	0.1797	0.0729
7	52	13.707	0.1344	1.0988	3.883	2378.252	0.9499	0.1299	

Flow rate of steam V_0 = 1.854 kg/s

Economy = (15.611 – 5.321)/1.854 = 5.549